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In this issue: Two articles on the use of fly ash in concrete.
(Garden State Parkway in New Jersey)

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IN THIS ISSUE

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Studies Relating to the Testing of Fly Ash for Use in Concrete

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported [1] by RUSSELL H. BRINK, Highway Physical Research Engineer, and WOODROW J. HALSTEAD, Chemist

Recent interest in the use of fly ash in concrete for highways has created a need for suitable specifications and methods of test for this material when it is used to replace part of the cement. The effect of fly ash on the strength of portland cement-fly ash mortars is considered to indicate the probable effect on the strength of concrete, and is used in this investigation as a criterion for evaluating other tests of fly ash. The effect of fly ash on the expansion resulting from the alkali-aggregate reaction is also considered. To determine the variations in properties which may be expected and the effect of these variations on the behavior of the fly ash in mortar, 34 fly ashes from 19 different sources were examined.

The results of the tests indicate generally that the strength developed in portland cement-fly ash mortars is related to the carbon content of the fly ash, the fineness of fly ash as measured by the amount passing the No. 325 sieve, and the water required for mortars containing fly ash as compared with the water required for similar mortars without fly ash. No well-defined relation between the individual inorganic constituents of the fly ash and the development of strength of the mortar was obtained.

These tests also indicate that the effect on the strength of mortar of replacing a portion of the cement with fly ash varies according to the cement used.

Tests of mortar bars show that fly ash may be used to inhibit the expansion resulting from the alkali-aggregate reaction. These tests indicate that the amount of fly ash required to reduce expansion below a safe limit varies for different fly ashes.

FLY ASH is a powdery residue resulting from the burning of pulverized coal. In modern power plants this material is collected at the entrance to the stack by electrical or mechanical precipitators to prevent pollution of the air. Fly ash is usually finer than portland cement and consists mostly of small spheres of glassy compounds of complex chemical composition together with miscellaneous materials such as quartz, feldspar, iron oxides, and carbon.[2] Photomicrographs of two fly ashes are shown in figure 1.

During recent years there has been a growing interest by both governmental and industrial organizations in the use of fly ash as an additive to concrete. A number of reports have been published which indicate that beneficial effects may be obtained when fly ash is used to replace a portion of either the sand or the cement (*1, 2, 3, 4*).[3] In an investigation of concrete for the Hungry Horse Dam, Blanks (*1*) reported that fly ash improved the workability and decreased the bleeding of plastic concrete. The segregation of aggregates in concrete was also decreased. In the hardening concrete it was found that a cement-fly ash combination produced less rise in temperature than an equal amount of portland cement. Other beneficial effects mentioned were decreased permeability, better resistance to sulfate attack, and reduced expansion resulting from the reaction between the alkalies of the cement and certain types of aggregate.

Fly ash has been used most extensively in mass concrete, particularly large dams, where many of the changes it produces in concrete are of value. As fly ash is less expensive than cement, its use to replace a portion of the cement has resulted in significant savings in the cost of certain projects. The possibility of reducing the cost of concrete for highway construction is responsible for much of the current interest by highway agencies in the use of fly ash. Interest has also been shown in its use at locations where the alkali-aggregate reaction is a problem.

Regardless of the primary reason for using fly ash in concrete, the effect of the admixture on the strength of the concrete must be considered. When fly ash is used to replace a portion of the cement, the strength of the resulting concrete is usually reduced at early ages but with adequate curing it may eventually equal or exceed that of concrete without fly ash (*1, 2*). Fly ash contributes to the strength of concrete at later ages because it is

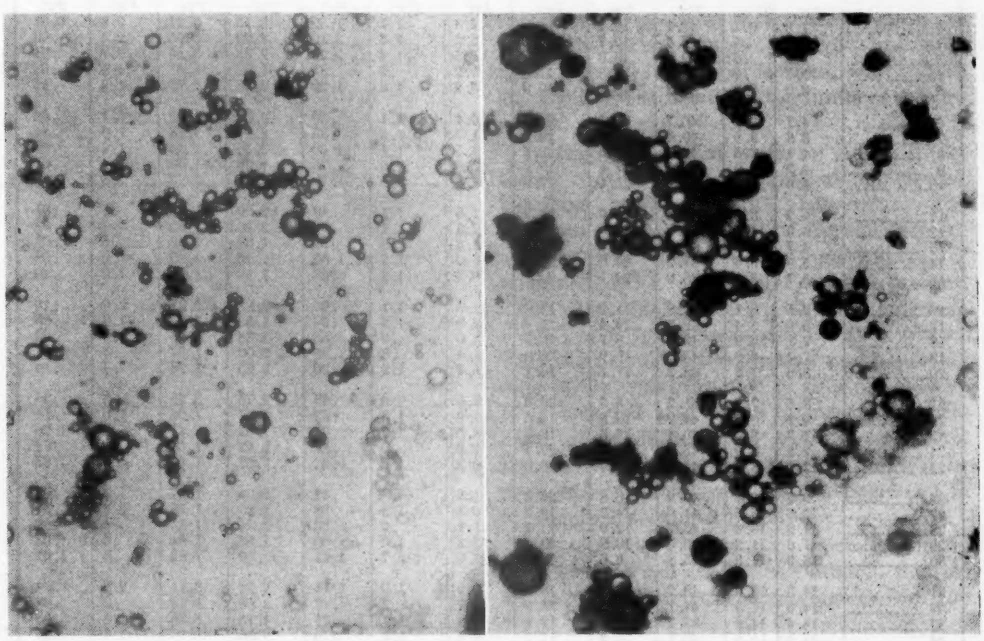

Figure 1.—Photomicrographs (×390) of two samples of fly ash having the following carbon content: No. 1 (left), 0.2 percent; and No. 15 (right), 5.5 percent.

[1] This article was presented at the 59th Annual Meeting of the American Society for Testing Materials, Atlantic City, N. J., June 17–22, 1956.

[2] A discussion of the nature and source of these materials and the chemical changes that occur during the burning of the coal is included as Appendix B on p. 140.

[3] Italic numbers in parentheses refer to the list of references on p. 141.

a pozzolanic material. A pozzolan is defined in ASTM Standard Definitions of Terms Relating to Hydraulic Cement, C 219–55, as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." The reaction between fly ash and the lime released by the hydration of cement develops slowly, and a minimum of 30 days may be required before the strength developed in concrete by this reaction will compensate for the initial loss in strength resulting from the lower cement content.

Fly ashes from different sources vary considerably in both chemical composition and physical properties due to differences between the coals from which they are derived and the conditions of burning. Consequently, it is to be expected that their behavior in concrete will not be uniform. This investigation was conducted primarily to study the pozzolanic behavior of fly ash as shown by its effect on the strength of cement mortar. The strengths developed in mortars containing fly ash were used to study the relations between pozzolanic activity and the various chemical and physical properties of fly ash. Comparisons were also made between the effect of fly ash on the strength of mortar and the results of other tests involving reaction of fly ash with lime or sodium hydroxide.

At the time this investigation was undertaken, it was generally recognized that finely divided, low-carbon fly ashes were useful as admixtures to concrete. However, there was no general agreement as to the limits which should be placed on these properties or the extent to which these properties alone could be relied upon for selecting fly ashes. It was hoped that the information obtained in this investigation would provide a suitable basis for the selection of fly ashes for use in concrete. A study was also made of the effectiveness of fly ash in reducing expansion resulting from the alkali-aggregate reaction. These results were considered separately from the general behavior of fly ash as a pozzolanic material.

To have fly ashes with a wide range of physical and chemical properties represented in this investigation, 34 samples produced by 12 different concerns at 19 individual plants were obtained. Fly ashes from the sources represented by samples 1, 3, 5, and 16 had been used in concrete with good results, but the use or quality of the other samples was not known. Four of the samples (1, 3, 14, and 29) were also used in an investigation in which the effect of fly ash was determined directly on concrete specimens. The results of that study are reported in a companion article.[4]

Conclusions

The results of this investigation show that many factors affect the development of strength in a cement-fly ash mortar as a result of pozzolanic action. It was found that this action is influenced not only by the character of the fly ash but also by the properties of the cement. A general relation was found between pozzolanic activity and several other properties of fly ash.

The following general conclusions appear to be justified:

1. The effect on mortar strength of replacing part of the cement with fly ash varies with the cement used.

2. Compressive strength tests conducted on cement-fly ash mortars at various ages and with different cement contents indicate that ultimately fly ash has the greatest proportional benefit to lean mixes, even though tests at 28 days generally show the reverse to be true.

3. The carbon in fly ash lowers the strength of mortar because it increases the amount of water required to obtain a workable consistency, and reduces the amount of the pozzolanically active constituents of the fly ash. However, only a general relation between carbon content and mortar strength was found since other properties of fly ash also affect the development of strength of mortar due to pozzolanic action.

4. Specific surface determined by the air permeability method is often used as a measure of fineness in fly ash specifications. No relation was found between the strength of cement-fly ash mortars and fineness determined by this method.

5. In general, the strength of cement-fly ash mortars varied with the fineness of the fly ash as determined with the No. 325 sieve, the finer fly ashes being associated with the higher strengths.

6. A general agreement was found between the effect of fly ash on the strength of mortar and the amount of water required to prepare the mortar. If the addition of fly ash required an increase in the amount of water needed to prepare mortar of a stated consistency, a decrease in the strength of the mortar resulted.

7. No agreement was found between the amount of any single inorganic constituent in fly ash and the efficacy of the fly ash as a pozzolanic material.

8. A method involving reaction of silica with sodium hydroxide has been used with some success for determining the quality of pozzolanic materials. This test was not found suitable for testing fly ash because the lime or calcium sulfate present in fly ash prevented the normal course of the reaction.

9. A lime absorption test, involving reaction of fly ash in a lime solution, gave no reliable data for predicting the pozzolanic activity of fly ash.

10. A test for the compressive strength of lime-fly ash mortars cured at a temperature of 130° F. failed to give results agreeing satisfactorily with the strengths of cement-fly ash mortars. It is possible that changes in the details of the lime-fly ash mortar test may improve the reliability of the test, and a further study of this method is considered advisable.

11. Fly ash will inhibit the volume change caused by the alkali-aggregate reaction if

[4] Fly ashes 1, 3, 14, and 29 are identified as A, B, X, and Y, respectively, in the article *Use of fly ash in concrete*, which appears in this issue.

Table 1.—Chemical analysis of fly ash samples (oven-dry basis)

Identification number	Loss on ignition, 600° C.	Carbon	Silicon dioxide SiO_2	Ferric oxide Fe_2O_3	Aluminum oxide Al_2O_3	Calcium oxide CaO	Magnesium oxide MgO	Sodium oxide Na_2O	Potassium oxide K_2O	Total alkalies as Na_2O	Sulfur trioxide SO_3	Carbon dioxide CO_2
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	1.2	0.2	47.1	19.2	18.2	7.0	1.1	1.80	2.15	3.21	2.8	0.01
2	1.0	.5	48.4	19.7	17.9	5.2	1.2	2.10	2.20	3.55	2.3	.03
3	1.2	.6	49.2	16.2	19.9	5.5	1.4	2.00	2.35	3.55	2.7	.04
4	1.7	.7	39.1	31.3	17.6	5.2	.9	.35	1.92	1.61	1.5	.08
5	3.0	2.3	47.2	19.1	19.3	5.2	1.3	1.22	2.38	2.79	1.9	.11
6	4.1	2.4	46.7	16.4	20.3	6.4	1.1	.50	2.00	1.82	2.1	.64
7	3.8	3.5	40.4	29.5	20.0	1.7	1.2	.35	2.17	1.78	1.0	.01
8	4.1	3.5	47.1	16.3	22.2	4.5	1.1	1.00	2.50	2.64	1.2	.07
9	4.2	3.9	36.5	27.1	19.7	7.8	1.3	.75	1.28	1.59	1.4	.07
10	4.0	3.9	38.5	25.4	17.9	8.3	1.0	.40	2.00	1.72	2.3	.13
11	4.2	3.9	48.3	18.0	23.9	1.8	1.1	.40	2.00	1.72	.5	.01
12	5.0	4.5	51.9	12.3	23.7	2.3	1.1	.40	2.20	1.85	.4	.02
13	4.7	4.8	45.3	19.3	26.1	1.6	.8	.22	1.80	1.40	.3	.03
14	5.4	5.0	41.2	20.6	22.1	6.0	1.2	1.00	1.42	1.93	.9	.04
15	5.7	5.5	38.9	24.1	20.7	6.4	1.2	.83	1.28	1.67	1.0	.10
16	7.5	6.1	44.8	11.2	18.4	11.6	1.1	.92	2.22	2.38	2.0	.10
17	6.9	6.4	42.2	19.4	22.4	4.3	1.2	.67	1.82	1.87	1.0	.05
18	7.1	6.9	49.2	8.7	26.7	3.6	.9	.58	2.38	2.15	.6	.03
19	7.4	6.9	45.3	16.9	26.0	1.4	.8	.25	2.00	1.57	.3	.01
20	8.6	7.8	48.2	17.7	16.1	5.2	1.2	.30	2.25	1.78	.3	.10
21	8.6	7.9	51.2	8.5	25.6	1.6	.9	.48	2.75	2.29	.3	.06
22	9.2	8.2	44.2	19.9	14.6	7.6	1.3	.32	1.07	1.62	1.0	.14
23	11.2	8.4	40.4	16.3	18.3	8.5	1.0	.70	1.62	1.77	1.7	1.26
24	9.2	8.9	45.3	18.6	22.4	1.5	.9	.67	1.42	1.60	.3	.03
25	12.0	8.9	44.6	12.6	20.0	6.2	1.2	.32	2.02	1.64	.9	1.27
26	9.2	9.1	48.9	8.8	28.3	1.2	.8	.52	2.20	1.97	.4	.02
27	12.5	10.5	41.6	14.2	19.0	6.8	1.2	.58	1.80	1.76	2.2	.51
28	11.2	10.6	46.7	12.9	24.7	1.1	.9	.50	2.05	1.85	.4	.02
29	11.6	11.2	38.5	18.8	23.5	3.2	1.0	.60	1.88	1.84	.6	.03
30	16.9	11.9	45.8	6.6	13.5	12.0	2.7	1.61	.50	1.94	.8	1.61
31	14.8	13.6	40.2	15.0	18.6	3.9	1.0	1.15	2.98	3.11	2.2	.04
32	14.5	14.3	44.1	10.9	25.5	1.7	.7	.47	2.00	1.79	.2	.04
33	16.4	14.8	32.7	28.0	17.1	1.8	1.1	.25	1.73	1.39	1.3	.03
34	18.0	15.6	40.1	15.2	17.5	3.5	1.1	.70	1.80	1.88	1.8	.15
Minimum	1.0	.2	32.7	6.6	13.5	1.1	.7	.22	.50	1.39	.2	.01
Maximum	18.0	15.6	51.9	31.3	28.3	12.0	2.7	2.10	2.98	3.55	2.8	1.61

Table 2.—Specific gravity and fineness of fly ash samples

Fly ash number	Apparent specific gravity	Fineness of fly ash samples				
		Amount passing—		Air permeability, specific surface	Hydrometer method	
		No. 200 sieve	No. 325 sieve		Specific surface	Amount smaller than 0.03 mm.
		Percent	*Percent*	*Cm.²/gm.*	*Cm.²/gm.*	*Percent*
1	2.49	96.8	93.2	3,075	4,050	76
2	2.49	95.0	92.1	3,295	5,105	79
3	2.52	98.6	95.2	4,305	5,570	86
4	2.69	94.6	90.0	2,550	3,130	67
5	2.46	97.4	95.3	3,585	3,115	87
6	2.38	96.2	92.1	3,960	3,085	74
7	2.62	94.4	91.7	3,775	3,290	76
8	2.44	96.8	93.9	4,290	3,520	81
9	2.65	95.6	92.9	3,110	2,475	75
10	2.58	95.4	91.7	4,250	4,070	81
11	2.36	88.2	83.2	3,030	1,390	47
12	2.37	93.2	88.9	3,580	3,715	71
13	2.32	82.0	75.8	2,960	2,025	48
14	2.51	91.8	84.5	2,565	2,770	59
15	2.50	85.8	81.3	2,845	930	50
16	2.39	95.2	93.2	5,355	2,080	94
17	2.52	94.2	91.5	4,020	2,330	56
18	2.31	92.4	89.3	4,060	2,565	68
19	2.33	90.2	86.4	3,830	2,450	61
20	2.40	90.8	81.6	2,560	-----	--
21	2.12	57.2	56.2	2,430	2,155	31
22	2.39	90.4	82.0	2,985	2,088	67
23	2.30	85.4	76.6	3,315	1,260	67
24	2.41	92.2	86.6	3,140	1,970	60
25	2.30	77.0	74.8	4,115	2,225	47
26	2.22	87.6	82.8	4,405	3,255	68
27	2.31	82.8	82.5	4,650	-----	--
28	2.24	85.0	81.9	4,295	1,965	50
29	2.43	93.8	89.4	3,220	2,000	66
30	2.20	33.1	----	-----	-----	--
31	2.42	96.0	93.2	4,795	2,435	79
32	2.25	87.2	80.9	4,400	2,250	51
33	2.44	81.5	76.1	3,860	1,795	38
34	2.29	81.0	78.1	4,610	2,230	62

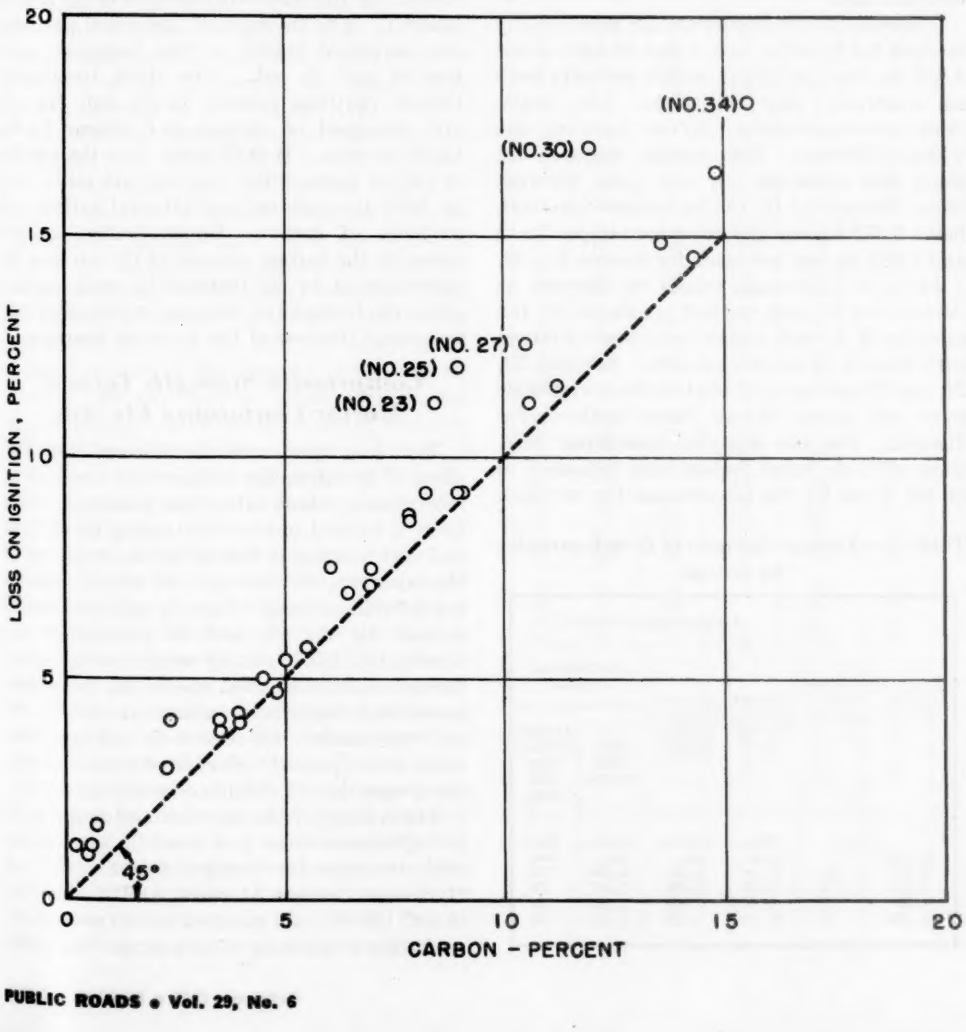

Figure 2 (Left).—Relation between carbon content and loss on ignition for 33 fly ashes.

used in sufficient amount. Because of variations in the behavior of different fly ashes, the amount to be used with a reactive combination of materials should be determined by testing concrete composed of those materials and the particular fly ash in question.

Chemical and Physical Properties of Fly Ash Samples

The results of chemical analyses showing the principal constituents of the samples of fly ash used in this investigation are given in table 1. In recognition of the importance of the carbon content of the fly ash, identification numbers were assigned to the samples on the basis of increasing amounts of carbon.

The carbon in fly ash represents unburned portions of the coal and varies with the conditions of burning at the plant. Some fly ashes are produced which contain more carbon than any of the samples listed in table 1, but such materials are not likely to be considered for use in concrete. Although the loss on ignition of fly ash is generally considered to be closely related to the carbon content, table 1 and figure 2 show that the loss can be considerably greater in some cases. Of these samples, five showed differences equal to or greater than 2.0 percent—the greatest difference being 5.0 percent for sample 30. These large differences usually occur when there is an appreciable amount of calcium hydroxide or carbonate present. At the ignition temperature used, 600° C., these materials decompose to the oxide and either water or carbon dioxide. As the latter two constituents are volatile they increase the loss on ignition. Combined moisture from other minerals may also increase the loss.

It should be noted that the practice of limiting the carbon content by specifying a maximum, limit for ignition loss will insure, for all practical purposes, that the carbon content will be less than this limit and sometimes by a significant amount. The one exception to this general statement is the case of sample 13 where the carbon content exceeds the loss on ignition by 0.1 of a percentage point. This small difference is within the limits of experimental error.

It is possible that some of the samples tested contain small amounts of manganese, titanium, and possibly phosphorus. The titanium and phosphorus, if present, are included with the reported percentage of alumina (Al_2O_3). When manganese is present, most of it is included with the magnesia (MgO) and the balance with the lime (CaO). This manner of determination and reporting follows the usual practice in silicate analysis. It is believed that these minor constituents have no significance in this investigation. Details of the methods followed in making the chemical analyses are given on page 139 in procedure 1 of Appendix A.

The specific gravity and fineness for all samples of fly ash are given in table 2. Sample 30 had only 33.1 percent passing the No. 200

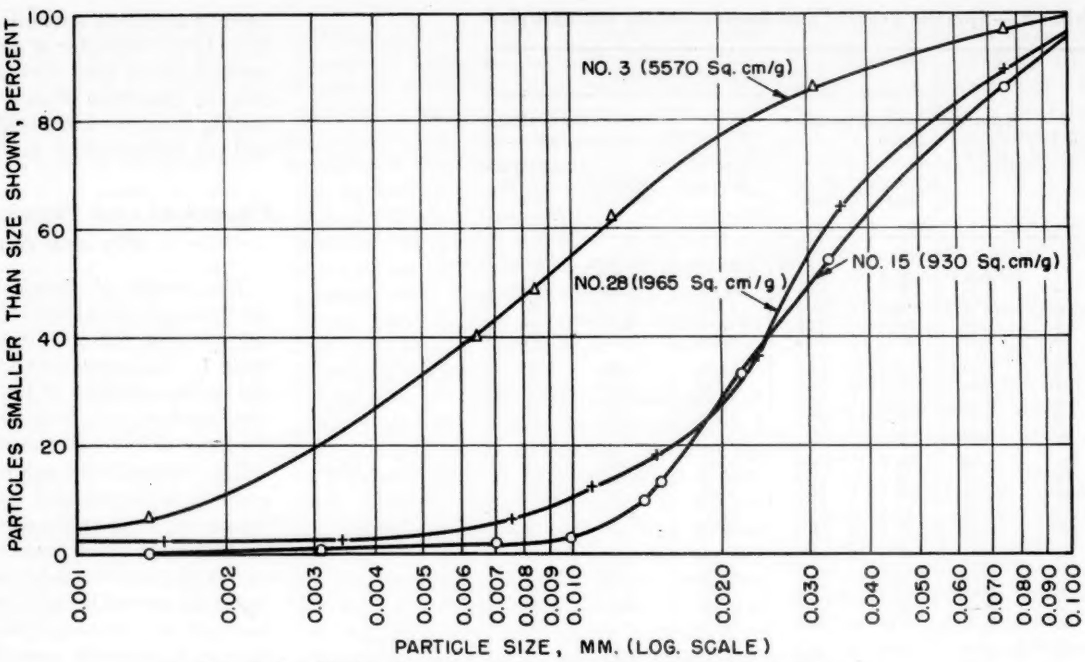

Figure 3.—Grain-diameter accumulation curves for 3 fly ashes.

sieve, and mortar tests were not made with this fly ash. The specific gravities of the fly ashes vary from 2.12 to 2.69 and are found to bear a general relation to the amounts of iron oxide present in the sample—high specific gravities being indicative of high iron contents.

The fineness of the fly ash was determined by three methods: wet sieving through the Nos. 200 and 325 sieves, air permeability, and hydrometer analysis. The amount passing the No. 325 sieve was determined in accordance with the procedure outlined in section 12 of the test for Fineness of Portland Cement by the Turbidimeter, ASTM Designation C 115–53. Specific surface by air permeability was determined by the test for Fineness of Portland Cement by Air Permeability Apparatus, ASTM Designation C 204–55. The weight of sample used in this test was determined by trial as the weight necessary to obtain a hard, firm bed in the permeability cell. For many samples it was found necessary to use a porosity for the test bed of fly ash which differed considerably from the porosity used in the calibration of the apparatus. Fineness by the hydrometer method was determined in accordance with the Standard Methods of Mechanical Analysis of Soils, AASHO Designation T 88–54, using 125 ml. of a 0.4N solution of sodium hexametaphosphate as the deflocculating agent. Dispersion cup A shown in figure 3 of the AASHO method was used. The initial weight of each sample was corrected for the amount of water-soluble material present in calculating the amount of sample smaller than each size.

The grain-diameter accumulation curve obtained by the hydrometer analysis was used to calculate the specific surface based on the amounts of the sample estimated to have average diameters of 0.7, 2, 3, 4, 5, 6, 7, 8, 9, 12, 20, 30, 40, 50, and 60 microns. The grain-diameter accumulation curves for three fly ashes are shown in figure 3. The curves for the remaining samples used in this investigation lie essentially within the area bounded by the curves for fly ashes Nos. 3 and 15, which have the highest and lowest specific surfaces, respectively, as calculated by this method. The curve for sample 28 is included to illustrate the discrepancy that is often shown between values for specific surface obtained by the air permeability and hydrometer methods.

The specific surfaces by the air permeability method for fly ashes Nos. 3 and 28 were about 4,300 sq. cm. per gram, which classifies both as relatively fine materials. The grain-diameter accumulation curves, however, are widely different. The specific surfaces for these two materials are also quite different when determined by the hydrometer method, being 5,570 sq. cm. per gram for sample No. 3 and 1,965 sq. cm. per gram for sample No. 28.

In table 3, average values for fineness as determined by each method are shown for the samples of fly ash which have been grouped with respect to carbon content. Samples 20, 27, and 30 are not included as these materials were not tested by all three methods for fineness. For the samples considered here, those with the most carbon were indicated to be the finest by the air permeability method.

Table 3.—Average fineness of fly ash samples by groups

Range of carbon content	Number of samples	Average fineness values			
		Amount passing No. 325 sieve	Air permeability, specific surface	Hydrometer method	
				Specific surface	Amount smaller than 0.03 mm.
Percent		*Percent*	*Cm.²/gm.*	*Cm.²/gm.*	*Percent*
0–4	11	91.9	3,570	3,530	75
4–8	9	83.0	3,520	2,340	60
8–12	7	82.0	3,640	2,110	61
12–15.6	4	81.0	4,420	2,180	58

Determinations of fineness by both the No. 325 sieve and the hydrometer showed, however, that the finest fly ashes were those containing relatively little carbon.

These data indicate that the determination of the fineness of fly ash by the air permeability method is likely to furnish misleading information. A possible cause of this can be seen by examining the photomicrographs of fly ash in figure 1. The transparent, spherical particles are composed chiefly of the inorganic portion of each fly ash. The dark, irregularly shaped particles present in fly ash No. 15 are composed of carbon and appear to be highly porous. It is believed that the results of the air permeability method are influenced by both the external and internal surfaces of particles of carbon. Consequently, an increase in the carbon content of fly ash may be accompanied by an increase in total surface area even though the external surface area and the actual fineness of the material decrease.

Compressive Strength Tests of Mortar Containing Fly Ash

The test specimens for determining the effect of fly ash on the compressive strength of mortar were 2-inch cubes, and were made both from a control mortar containing no fly ash and test mortars in which various amounts of the same cement were replaced with fly ash on a solid volume basis. Each fly ash was used to replace 10, 20, 35, and 50 percent of the cement in a 1:2.75 mix by weight using graded Ottawa sand. Control specimens were prepared each day that specimens containing fly ash were made. All cement-fly ash combinations were repeated with each of three cements, the properties of which are given in table 4.

The mixing of the mortars and molding of the specimens were performed in accordance with the test for Compressive Strength of Hydraulic Cement Mortars, ASTM Designation C 109–49. As specified in this procedure, a uniform consistency of all mortars was main-

Table 4.—Properties of cements used in preparing mortars containing fly ash

	Cement A	Cement B	Cement C
Chemical analysis (in percent):			
Silicon dioxide (SiO_2)	21.8	22.3	21.7
Aluminum oxide (Al_2O_3)	5.7	5.4	6.1
Ferric oxide (Fe_2O_3)	2.5	2.4	2.8
Calcium oxide (CaO)	61.9	66.1	64.9
Magnesium oxide (MgO)	2.6	1.0	1.2
Sulfur trioxide (SO_3)	1.9	1.7	1.6
Loss on ignition	2.1	1.2	1.2
Insoluble residue	.19	.12	------
Sodium oxide (Na_2O)	.33	.04	.13
Potassium oxide (K_2O)	.86	.15	.72
Equivalent alkali as Na_2O	.90	.13	.60
Compound composition (in percent):			
Tricalcium silicate (C_3S)	39	55	50
Dicalcium silicate (C_2S)	33	22	25
Tricalcium aluminate (C_3A)	11	10	12
Physical Properties:			
Fineness (Wagner turbidimeter) ... cm²/gm	1,785	1,625	1,875
Normal consistency ... percent	24.5	25.0	25.5
Air content of mortar ... do	10.0	6.8	7.8
Compressive strength[1]:			
At 7 days ... p. s. i.	2,260	2,960	4,325
At 28 days ... do	3,560	4,725	6,000
Time of set:			
Initial ... hours	2.6	4.2	4.0
Final ... do	4.0	6.4	5.1

[1] ASTM Method C 109.

tained by adjusting the amount of water added to each mix. The effect of a particular fly ash on the amount of mixing water required can be indicated conveniently by calculating the ratio of the amount of water required by the cement-fly ash mortar to that required by the control mortar. This ratio will be referred to subsequently as "water requirement ratio." After removal from the molds at an age of 24 hours, all specimens were stored at 73° F. in moist air in tightly covered containers until tested at ages of 28, 91, and 365 days.

The water requirement ratios used for preparing the mortars containing fly ash are given in table 5. The results of the tests for compressive strength of these mortars are given in tables 6–8 (pp. 128–130). For the convenience of the reader, the actual average strengths obtained in tests of the control mortars (without fly ash) are given, but the strengths of the mortars containing fly ash are reported as ratios (percent) of the strength of the control mortar. By this means, direct comparisons can be made to study the effect of any variable included in these tests. Figures 4 and 5 show averages of the compressive strength ratios obtained with the three cements for each fly ash.

As shown in tables 6–8 and figures 4–5, an increase in age of test is usually accompanied by an increase in strength ratio. This is assumed to indicate that each fly ash tested has some pozzolanic properties. The few results which do not follow this general trend are believed to be instances where the effects of pozzolanic action have been overshadowed by other experimental variations.

The replacement of part of the cement by fly ash usually resulted in some loss of strength at an age of 28 days, since at this age sufficient pozzolanic action had not taken place to compensate for the reduction in strength caused by the use of less cement. This early loss in strength became greater as the amount of replacement of cement by fly ash was increased. At greater ages, however, some fly ashes furnished sufficient pozzolanic activity to overcome this early deficiency in strength. The general decrease in strength ratio with increase in the carbon content of the fly ash is also of interest, as well as the individual fly ashes which gave results departing from this trend.

Effect of Richness of Mix

As shown in tables 6–8, four fly ashes, Nos. 1, 3, 14, and 29, were tested in 1:2, 1:2.75, and 1:3.5 mortars. The average results of tests of these mortars obtained with a 35-percent replacement of the three cements are shown in figure 6 (p. 131). For three of the four fly ashes, the richest mix showed the least reduction in strength ratio at an age of 28 days and the leanest mix showed the most. For the fourth fly ash, the strength ratios at 28 days were practically the same. At an age of 1 year, however, the leanest mix showed the greatest strength ratio for all fly ashes. This shows that ultimately fly ash may be of most value in the leaner mortars and concretes. Similar results have been found with the use of various pozzolans in concrete (*5*).

Influence of Cement Characteristics

The characteristics of the cements used had a marked effect on the strength ratio of mortar containing fly ash. The effect of differences in cement is illustrated by the graphs of figure 7 (p. 131) which show the age-strength relations obtained for a 35-percent replacement with each of three fly ashes of different carbon content and also the average of the strength ratios obtained with 33 fly ashes. The use of cement A produced appreciably higher strength ratios than cement B with all fly ashes. With few exceptions, mortars prepared with cement C produced strength ratios intermediate between those shown for mortars containing cements A or B.

To investigate further the variations in strength ratios which might occur because of differences in cements, compressive strength specimens were prepared with 10 cements other than those previously used. In each case, a 1:2 mortar was prepared with fly ash

Table 5.—Water requirement ratio of cement-fly ash mortars

Fly ash number	Water requirement ratio based on control mortar											
	10-percent replacement			20-percent replacement			35-percent replacement			50-percent replacement		
	Cement A	Cement B	Cement C	Cement A	Cement B	Cement C	Cement A	Cement B	Cement C	Cement A	Cement B	Cement C
1:2.75 MORTAR												
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	96	94	94	93	93	92	90	90	89	86	86	85
2	100	100	101	97	96	99	92	91	94	88	87	89
3	96	94	94	93	93	92	90	90	89	87	87	85
4	103	101	101	97	99	69	92	97	97	91	96	95
5	101	100	101	97	97	97	94	94	93	90	91	90
6	101	101	101	99	99	99	97	100	97	101	101	101
7	104	103	103	104	103	102	103	101	100	103	103	100
8	101	101	102	100	101	100	97	99	97	94	94	95
9	100	101	102	100	101	102	99	100	100	97	99	98
10	100	99	102	100	100	102	100	101	103	100	101	103
11	104	103	103	101	104	101	104	101	101	103	101	103
12	101	100	102	98	100	100	97	99	98	94	97	97
13	100	100	102	101	103	105	103	104	106	104	109	111
14	101	100	100	101	100	100	101	100	100	103	100	101
15	101	103	103	104	104	105	106	107	106	107	109	109
16	103	100	101	100	97	99	97	94	96	94	93	94
17	98	100	101	97	101	100	97	101	101	97	101	101
18	102	99	103	102	100	101	102	100	101	102	100	101
19	98	103	103	98	103	105	98	103	105	102	106	108
20	100	100	100	98	101	100	98	100	101	98	101	101
21	102	100	101	106	106	108	112	113	116	118	122	125
22	102	103	103	103	106	106	108	110	111	111	113	124
23	100	101	100	100	103	101	102	106	104	105	109	107
24	100	100	98	102	103	101	103	104	103	106	106	106
25	101	101	101	103	104	104	109	109	109	116	115	116
26	100	103	103	102	107	108	105	109	112	109	113	116
27	107	107	107	109	109	109	118	118	115	125	125	119
28	104	104	101	106	104	106	110	109	109	118	115	115
29	101	101	101	103	103	103	106	103	104	108	106	106
31	100	99	99	99	99	97	97	99	97	99	100	99
32	103	103	101	104	106	104	109	109	109	113	113	113
33	101	104	101	106	109	107	113	119	117	122	126	125
34	109	109	109	118	116	116	125	125	125	134	134	137
1:2 MORTAR												
1	99	97	97	94	93	93	89	89	89	84	84	85
3	96	99	99	92	93	94	86	90	92	82	86	87
14	100	101	100	102	100	100	101	100	100	101	100	100
29	100	101	100	100	103	101	105	106	104	110	109	107
1:3.5 MORTAR												
1	99	97	97	95	95	93	91	92	91	88	89	88
3	97	97	96	95	95	93	91	92	91	88	89	87
14	101	97	100	101	99	100	101	99	100	101	100	100
29	101	101	101	104	103	103	107	105	104	108	107	105

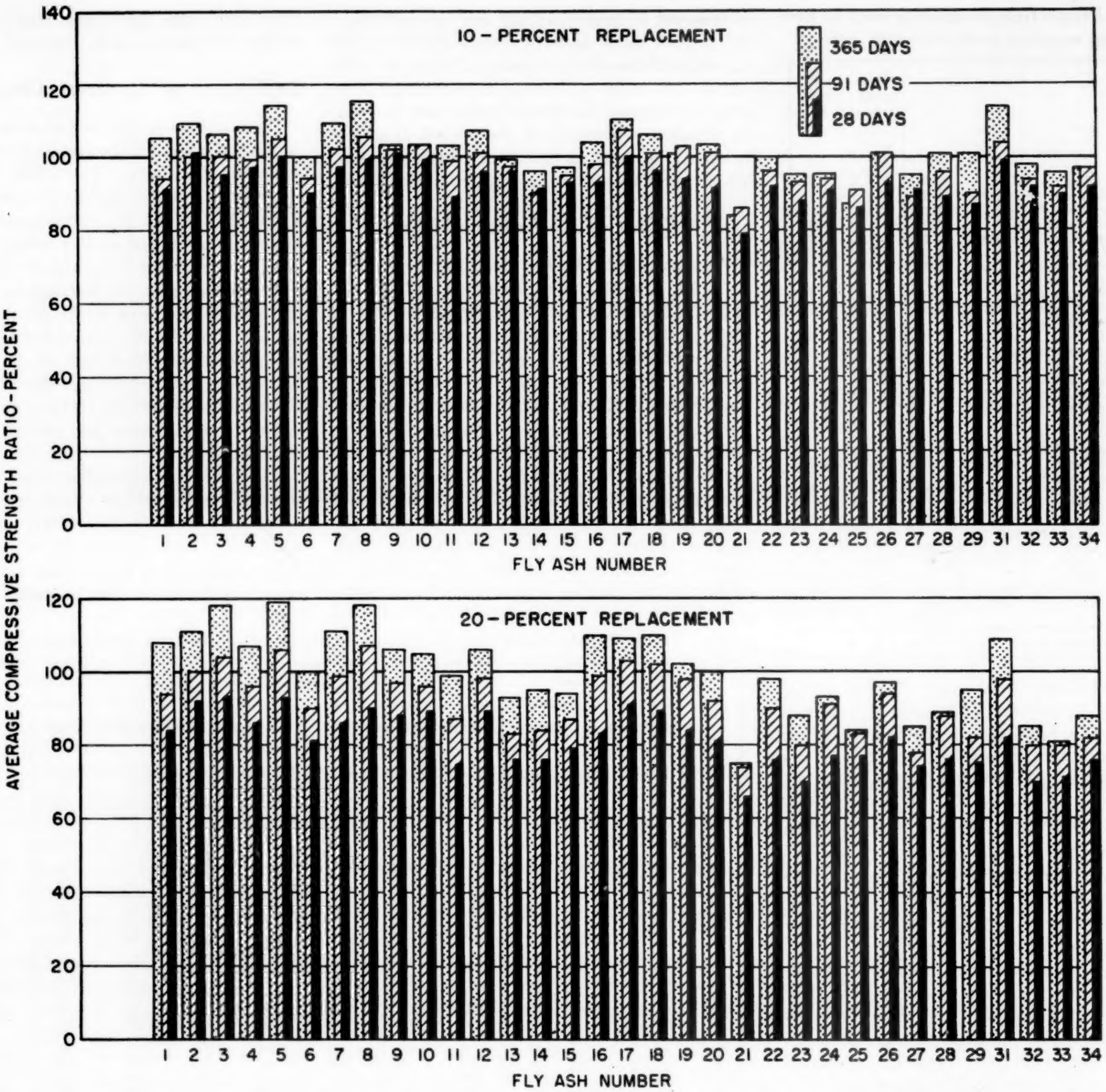

Figure 4.—Development of compressive strength in cement-fly ash mortar (1:2.75 mix, 10- and 20-percent replacement of cement with fly ash).

No. 3 replacing 50 percent of the cement. The cements were selected to provide a wide range in alkali content, tricalcium silicate content, and mortar strength. Cements A, B, and C also varied considerably in these properties. The results obtained with the 10 cements are shown in table 9 (p. 132). As in the previous tests, a wide range in compressive strength ratios was found for the single fly ash used.

The samples of cement in this table have been separated into three groups on the basis of their alkali content. As shown in figure 8 (p. 132) the rate of gain in strength ratio for the groups of mortars prepared with high, medium, and low alkali cements was influenced by the alkali content of the cements. The mortars prepared with high alkali cement reached maximum strength ratios at some age between 28 and 91 days. Those prepared with medium alkali cement required about 91 days to gain a maximum strength ratio. The mortars prepared with the cements of the low alkali group appeared to be still gaining in strength ratio when the test was terminated at an age of one year.

Davis (*5*) has stated that a larger replacement of cement by a pozzolan may be made when type I or II cement is used than when type IV cement is used. Types I and II cements contain more tricalcium silicate than type IV and should liberate more lime which can combine with the pozzolan. To check this hypothesis, the data given in table 9 were rearranged on the basis of the tricalcium silicate content of the cements and placed in groups in which the average tricalcium silicate content of the cement was 31, 45, and 60 percent. The age-strength data for these groups are shown in figure 9 (p. 132). At an age of one year, when the strength resulting from pozzolanic action would be more fully developed for all cements than at early ages, the strength ratios of the three groups of cement vary directly with the tricalcium silicate content. At ages less than one year, no definite relation between strength and tricalcium silicate is apparent.

The data given in table 9 and figures 8–9 indicate that the cement used has a marked effect on the development of strength from pozzolanic action in a cement-fly ash mortar. At the earlier ages of test, the alkali in the cement appears to accelerate the reaction between the cement and the fly ash. This agrees with data reported by Alexander (*6*). At the greater ages of test, the type of cement or more definitely, the amount of tricalcium silicate in the cement appears to govern the benefits derived by the addition of fly ash to the mortar.

Pozzolanic Strength Index

To determine the relations existing between the strength of cement-fly ash mortars and the properties of fly ash, it was necessary to select one standard of comparison for the strength of the mortar. The strength ratios

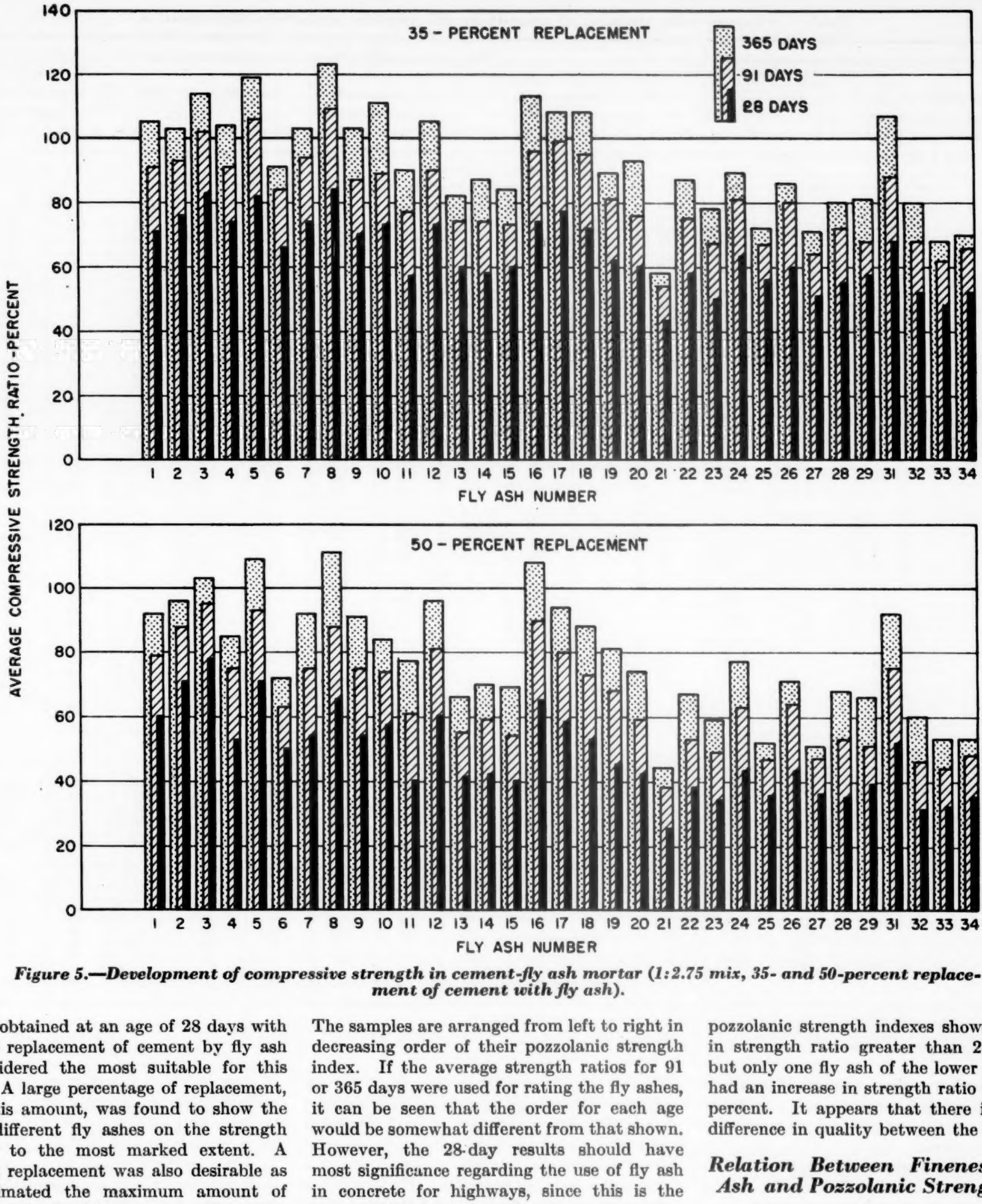

Figure 5.—Development of compressive strength in cement-fly ash mortar (1:2.75 mix, 35- and 50-percent replacement of cement with fly ash).

of mortar obtained at an age of 28 days with 35-percent replacement of cement by fly ash were considered the most suitable for this purpose. A large percentage of replacement, such as this amount, was found to show the effect of different fly ashes on the strength of mortar to the most marked extent. A 35-percent replacement was also desirable as it approximated the maximum amount of fly ash generally used in concrete. To obtain the most dependable value for assessing the quality of each fly ash, it appeared desirable to average the results for the three cements used. The average of the strength ratios obtained for each fly ash at an age of 28 days with 35-percent replacement of each of the three cements will be referred to in the remainder of this article as the "pozzolanic strength index."

The pozzolanic strength indexes of the 33 fly ashes are plotted in figure 10 (p. 133) together with averages of the strength ratios obtained for the same mortars at 91 and 365 days. The samples are arranged from left to right in decreasing order of their pozzolanic strength index. If the average strength ratios for 91 or 365 days were used for rating the fly ashes, it can be seen that the order for each age would be somewhat different from that shown. However, the 28-day results should have most significance regarding the use of fly ash in concrete for highways, since this is the age at which final strength tests are customarily made and at which the concrete may be placed in service.

It should be noted, moreover, that a high pozzolanic strength index generally indicates a continued high level of strength development. To illustrate, the 13 fly ashes having pozzolanic strength indexes of 70 or greater showed an average increase in strength ratio of 33.7 percent from 28 to 365 days, whereas the 20 fly ashes having indexes of less than 70 showed an average increase of only 25.4 percent during the same period. All of the 13 fly ashes in the group having the higher pozzolanic strength indexes showed increases in strength ratio greater than 25.4 percent, but only one fly ash of the lower index group had an increase in strength ratio of over 33.7 percent. It appears that there is a marked difference in quality between the two groups.

Relation Between Fineness of Fly Ash and Pozzolanic Strength Index

A high degree of fineness is generally desired for any pozzolanic material used as an admixture in concrete. In this series of tests, the fineness of nearly all fly ashes was determined by three methods: air permeability, hydrometer, and wet sieving through the Nos. 200 and 325 sieves. The results obtained are shown in table 2 and are also plotted against the pozzolanic strength index in figure 11 (p. 133).

No significant relation was found between the specific surface as determined by the air permeability or hydrometer methods and the pozzolanic strength index. Even for fly

Table 6.—Compressive strength of cement-fly ash mortars prepared with cement A [1]

Fly ash number	Compressive strength of control mortar (without fly ash) [2]			Compressive strength ratio of mortars containing fly ash [3]											
				10-percent replacement			20-percent replacement			35-percent replacement			50-percent replacement		
	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days
							1:2.75 MORTAR								
	P. s. i.	*P. s. i.*	*P. s. i.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	3,180	3,840	4,240	92	94	113	90	100	121	82	101	110	72	84	90
2	3,760	4,440	4,940	100	98	112	95	104	117	84	100	106	80	94	98
3	3,180	3,840	4,240	97	99	111	98	110	126	97	116	123	95	105	111
4	3,420	3,770	4,440	101	108	118	96	106	119	82	103	112	64	93	90
5	3,000	3,630	4,120	112	117	121	102	117	124	102	127	135	93	112	115
6	3,360	3,780	4,290	96	100	101	91	99	113	82	94	103	67	76	79
7	3,420	3,770	4,440	108	115	118	99	116	126	86	112	113	65	89	95
8	3,420	3,770	4,440	107	115	125	101	120	130	96	126	131	87	114	122
9	3,760	4,440	4,940	97	100	102	86	97	108	76	98	111	62	89	102
10	3,540	4,120	4,710	96	99	97	95	99	111	83	99	108	72	82	87
11	3,440	4,110	4,400	96	101	110	82	90	105	65	87	103	51	74	87
12	3,680	4,170	4,590	94	103	112	88	106	113	83	105	112	67	93	97
13	3,540	4,120	4,710	95	96	99	75	84	90	64	84	88	45	61	71
14	3,330	3,940	4,550	90	93	99	75	86	94	60	77	89	47	68	77
15	3,760	4,440	4,940	89	93	93	81	89	95	67	80	89	51	68	77
16	3,440	4,110	4,400	103	102	112	95	114	127	95	121	138	91	114	124
17	3,520	3,830	4,580	104	113	112	96	107	108	87	117	118	75	97	102
18	3,740	4,450	4,750	95	100	103	90	103	115	86	108	121	64	82	105
19	3,520	3,830	4,580	95	105	98	88	108	108	72	96	100	58	86	96
20	3,740	4,450	4,750	94	101	101	85	96	108	66	81	103	45	63	78
21	3,740	4,450	4,750	78	82	84	72	75	81	53	60	66	30	44	48
22	3,520	3,830	4,580	96	99	99	86	100	105	68	88	95	46	67	73
23	3,800	4,020	4,490	88	96	98	75	88	96	54	75	85	42	56	65
24	3,520	3,830	4,580	92	100	100	88	101	98	71	96	94	56	81	88
25	3,360	3,780	4,290	92	93	93	84	90	89	62	74	76	42	52	52
26	3,520	3,830	4,580	94	108	107	92	109	110	69	93	94	54	81	84
27	3,000	3,630	4,120	98	94	97	83	85	89	62	76	82	41	51	52
28	3,440	4,110	4,400	93	101	111	86	98	105	66	85	95	44	65	81
29	3,330	3,940	4,550	84	91	95	73	81	93	60	76	84	46	60	74
31	3,520	3,990	4,560	108	111	114	91	109	116	80	109	115	70	99	105
32	3,520	3,990	4,560	95	101	98	78	89	93	64	83	92	39	59	74
33	3,520	3,990	4,560	94	90	93	81	91	89	60	76	79	41	56	64
34	3,000	3,630	4,120	93	100	97	85	93	92	67	82	80	44	56	58
Average	------	------	------	96	101	104	87	99	106	74	94	102	59	78	85
							1:2 MORTAR								
1	4,670	5,340	5,890	102	102	113	99	108	124	97	115	119	92	104	114
3	4,560	5,490	6,510	102	103	108	103	115	115	109	121	114	114	117	109
14	4,960	5,800	6,840	96	102	104	80	87	94	63	80	86	54	73	78
29	4,960	5,800	6,840	95	104	102	75	92	100	64	81	91	44	64	75
Average	------	------	------	99	103	107	89	100	108	83	99	102	76	90	94
							1:3.5 MORTAR								
1	2,540	2,950	3,170	97	108	117	83	97	124	73	98	121	61	88	103
3	2,540	2,950	3,170	92	100	113	92	107	133	91	110	136	82	103	117
14	2,540	2,950	3,170	88	97	103	78	67	76	57	82	108	42	68	98
29	2,330	2,920	3,000	105	106	133	95	97	122	72	85	109	51	61	88
Average	------	------	------	96	103	116	87	92	114	73	94	118	59	80	102

[1] Moist air storage at 73° F.
[2] Each value is an average of three 2-inch cubes.
[3] Reported as a percentage of the strength of control mortar.

ashes having low carbon contents (5.0 percent or less), no definite correlation was found between strength and specific surface. The amount of material passing the No. 325 sieve, however, showed a reasonably definite relation to the pozzolanic strength index. In view of the results obtained with the No. 325 sieve, data from the hydrometer determinations were used to obtain values for amounts of each sample finer than the 0.03, 0.025, 0.02, and 0.01 mm. sizes. Correlation with the pozzolanic strength index was found to be best when the size finer than 0.03 mm. was used, but became poorer with the smaller sizes in the group.

Relation Between Carbon and the Pozzolanic Strength Index

Minnick (7) has shown that the strengths of fly ash-cement mortars are adversely affected by fly ashes having high carbon contents. In general, the data shown in tables 6–8 support these findings. A similar trend is evident in figure 12 (p. 134) in which the relation between the pozzolanic strength index and carbon content is shown. The scattering of points in this figure indicates the effect of variables other than carbon. For example, fly ashes 21 and 31 appear to have properties which cause them to deviate significantly from the general trend. The rather low strength index value of sample 21 may be partly attributed to an unusual coarseness of the fly ash and high water requirement of the mortar prepared with this material. Although sample 31 contained 13.6 percent carbon, its high fineness and low water requirement probably account for the high strength index.

The effect of carbon content on the strength of mortar was investigated in a special series of tests in which five selected fly ashes having carbon contents ranging from 0.2 to 14.3 percent were tested before and after heating to a temperature of 550° C. This temperature is considered sufficient to remove all the carbon, and although some oxidation of ferrous iron to the ferric state may have occurred, it is believed that the pozzolanic properties of the inorganic portion of the fly ash were unaltered.

Strength tests were conducted on control specimens prepared from a 1:2.75 mortar and test specimens in which a portion of the cement was replaced with fly ash by three different methods as follows:

1. Thirty-five percent of the solid volume of cement used in the control mortar was replaced by an equal volume of fly ash as received.

2. Thirty-five percent of the solid volume of cement used in the control mortar was

Table 7.—Compressive strength of cement-fly ash mortars prepared with cement B [1]

Fly ash number	Compressive strength of control mortar (without fly ash) [2]			Compressive strength ratio of mortars containing fly ash [3]											
				10-percent replacement			20-percent replacement			35-percent replacement			50-percent replacement		
	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days
1:2.75 Mortar															
	P. s. i.	*P. s. i.*	*P. s. i.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	5,130	6,260	7,030	92	92	98	82	93	102	66	84	97	51	75	87
2	5,020	6,360	6,560	108	105	113	92	97	107	67	85	97	63	79	87
3	5,130	6,260	7,030	95	103	105	93	101	113	75	93	107	69	89	98
4	4,840	6,000	6,440	99	93	103	88	95	103	72	89	105	46	63	76
5	5,150	6,190	6,780	94	100	108	88	97	113	69	91	111	55	76	98
6	5,560	6,730	6,930	83	83	94	70	76	88	54	76	83	35	50	66
7	5,290	6,240	6,390	90	92	99	78	88	101	65	84	94	45	67	92
8	5,290	6,240	6,390	88	95	104	81	94	107	74	97	121	45	70	102
9	4,840	6,000	6,440	99	101	105	81	89	104	56	70	92	46	68	87
10	4,840	6,000	6,440	105	107	109	87	93	105	66	82	97	46	67	77
11	5,220	6,410	7,040	83	91	91	67	80	90	48	65	77	33	50	64
12	5,020	6,360	6,560	97	99	101	80	82	94	63	78	98	53	72	93
13	4,840	6,000	6,440	99	100	101	77	86	94	51	66	76	35	50	60
14	4,930	6,290	6,620	92	86	95	75	79	93	55	69	85	36	51	62
15	4,840	6,000	6,440	91	98	102	72	81	93	48	63	80	28	40	62
16	5,220	6,410	7,040	87	95	97	74	86	96	57	78	96	47	72	92
17	4,760	5,540	5,870	92	100	108	85	101	114	65	86	101	43	64	86
18	5,030	6,040	6,540	87	95	100	79	90	104	58	78	95	40	61	82
19	4,910	5,770	6,260	87	100	104	79	89	95	58	74	86	37	51	71
20	4,760	5,540	5,870	86	97	107	75	85	100	54	70	88	38	52	73
21	5,030	6,040	6,540	73	81	80	58	67	69	33	45	51	20	33	41
22	4,760	5,540	5,870	86	94	103	65	78	91	51	68	85	31	45	66
23	4,840	5,900	6,590	89	92	93	68	73	81	47	60	72	29	42	51
24	4,840	5,900	6,500	97	93	98	72	90	92	59	73	82	37	51	67
25	5,560	6,730	6,930	75	82	72	71	75	80	49	57	65	26	39	49
26	4,840	5,900	6,590	94	98	98	76	88	90	54	74	83	37	56	64
27	5,150	6,190	6,780	85	78	90	66	71	84	43	56	65	28	40	47
28	5,220	6,410	7,040	87	92	97	70	81	85	44	61	69	26	41	55
29	4,930	6,290	6,620	87	89	100	73	77	91	53	60	75	33	44	57
31	5,220	6,640	6,930	92	95	106	77	91	105	60	71	96	37	51	73
32	5,220	6,640	6,930	84	85	93	63	72	78	44	57	70	25	36	48
33	5,220	6,640	6,930	83	88	93	64	73	79	40	53	61	23	34	44
34	5,150	6,190	6,780	92	92	96	68	70	87	41	55	62	28	41	49
Average	------	------	------	90	94	99	76	84	95	56	72	86	39	55	70
1:2 Mortar															
1	8,440	10,390	10,970	87	93	99	82	89	96	70	85	99	60	71	81
3	8,560	10,260	10,960	94	97	108	87	100	108	82	95	107	76	83	91
14	8,440	10,390	10,970	90	91	101	71	82	92	56	64	80	40	49	62
29	8,440	10,390	10,970	92	93	101	76	80	89	53	60	74	33	43	57
Average	------	------	------	91	94	102	79	88	96	65	76	90	52	62	73
1:3.5 Mortar															
1	3,260	4,270	4,500	85	98	113	71	90	103	58	79	100	42	65	94
3	3,260	4,270	4,500	86	93	107	77	88	106	63	78	107	52	71	97
14	3,260	4,270	4,500	75	84	93	60	70	87	43	60	74	28	44	64
29	3,320	4,140	4,540	86	90	96	71	79	90	51	64	78	31	43	53
Average	------	------	------	83	91	102	70	82	96	54	70	90	38	56	77

[1] Moist air storage at 73° F.
[2] Each value is an average of three 2-inch cubes.
[3] Reported as a percentage of strength of control mortar.

replaced by an equal volume of ignited fly ash. This replacement resulted in more inorganic material being added to the mix than by the first method.

3. Thirty-five percent of the solid volume of cement used in the control mortar was replaced by a smaller volume of ignited fly ash equal to that of the inorganic portion of the fly ash added by the first method. The replacement in this case did not result in a 1:2.75 mix but one in which the cement, sand, and inorganic constituents from the fly ash were the same as for the mortar in method 1.

The water requirement and strength ratios for this series are shown in table 10 (p. 135). The results obtained with fly ash No. 1 were essentially the same for the three methods of replacement, which indicates that the pozzolanic properties of this fly ash were not changed by ignition at 550° C. No effect would be expected to result from the removal of the 0.2 percent carbon originally present in this sample. An explanation of the strength ratios obtained with fly ash No. 7 is not apparent.

For the remaining three samples, the strength ratios were highest when replacement was made by method 2 which provided the greatest amount of carbon-free fly ash, and lowest by method 1 where carbon was present in the fly ash. The direct effect of the carbon is found by comparing the results obtained by methods 1 and 3 since the amount of the inorganic constituent is the same in either case. The slightly lower strengths obtained by method 1 where carbon was present can be attributed to the higher water requirements of these mortars. The higher strengths obtained by method 2 as compared with method 3 must result from the greater quantity of carbon-free ash added by that method since no carbon is present in either case. The range in strength ratios at 28 days from 71 to 87 percent which was found for the five fly ashes tested by method 2 also indicates that essential differences exist between the fly ashes which cannot be attributed to their carbon content.

These results indicate that the carbon in fly ash has at least two adverse effects on the strength of mortar. Some reduction in strength occurs as a result of the increased water requirement of the mortar caused by the presence of carbon. A reduction in strength also appears to result from the fact that the amount of beneficial inorganic material added to the mix is reduced by the amount of carbon present.

Relation of Water Requirement to Pozzolanic Strength Index

In the preparation of the mortars for the compressive strength tests, it was found that

Table 8.—Compressive strength of cement-fly ash mortars prepared with cement C [1]

Fly ash number	Compressive strength of control mortar (without fly ash) [2]			Compressive strength ratio of mortars containing fly ash [3]											
				10-percent replacement			20-percent replacement			35-percent replacement			50-percent replacement		
	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days	28 days	91 days	365 days
1 : 2.75 Mortar															
	P. s. i.	*P. s. i.*	*P. s. i.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	5,920	6,240	6,590	90	96	103	79	89	102	64	87	107	58	79	98
2	5,390	5,670	6,070	96	97	101	89	99	108	76	94	106	69	90	104
3	5,920	6,240	6,590	92	99	102	89	102	114	76	98	113	70	91	101
4	5,490	5,870	5,860	90	96	103	75	87	99	67	82	96	50	68	89
5	5,670	5,740	5,770	94	99	114	89	104	119	74	100	117	66	90	13
6	5,250	5,270	5,530	92	100	104	81	95	100	61	83	87	48	64	71
7	5,490	5,870	5,860	94	100	111	81	94	105	72	87	102	52	70	88
8	5,490	5,870	5,860	101	106	117	89	107	118	83	105	117	62	81	108
9	4,900	5,420	5,790	107	104	103	97	106	106	77	94	107	53	68	83
10	5,490	5,870	5,860	96	104	102	85	95	99	69	85	87	52	74	87
11	6,100	5,970	6,190	89	104	109	77	92	102	58	80	89	36	58	79
12	5,390	5,670	6,070	98	102	108	93	106	112	73	86	105	59	79	98
13	5,490	5,870	5,860	93	96	97	76	79	95						
13	4,900	5,420	5,790							65	73	82	43	55	68
14	5,440	5,610	5,640	90	92	94	79	87	98	59	75	86	43	59	72
15	4,900	5,420	5,790	98	95	94	84	92	93	65	75	83	41	54	69
16	6,100	5,970	6,190	88	98	102	80	98	108	71	90	106	58	83	108
17	5,080	5,360	5,650	104	107	111	92	102	106	80	93	105	57	78	94
18	5,410	5,220	5,750	103	107	115	97	112	112	73	98	108	55	76	88
19	5,080	5,360	5,650	99	103	103	85	98	102	57	72	81	41	67	77
20	5,410	5,220	5,750	93	104	101	82	95	104	60	77	89	42	61	72
21	5,410	5,220	5,750	85	95	88	67	79	75	42	58	57	25	38	42
22	5,080	5,360	5,650	93	96	99	78	93	97	56	69	80	36	47	63
23	5,570	5,640	5,940	87	92	93	67	79	86	49	67	78	31	48	62
24	5,570	5,640	5,940	85	90	87	72	82	90	59	74	91	36	57	75
25	5,250	5,270	5,530	91	98	95	76	84	83	58	71	75	37	50	55
26	5,080	5,360	5,650	92	97	97	77	86	91	57	73	81	37	54	65
27	5,670	5,740	5,770	90	96	97	72	77	82	49	59	65	38	50	55
28	6,100	5,970	6,190	86	95	95	72	85	88	54	69	77	36	54	67
29	5,440	5,610	5,640	89	91	109	80	87	101	58	68	85	38	50	67
31	5,540	5,500	5,490	98	105	111	79	93	106	65	85	109	48	74	97
32	5,540	5,500	5,490	91	97	102	69	78	84	47	63	79	28	42	58
33	5,540	5,500	5,490	94	97	102	68	75	75	44	56	64	31	42	50
34	5,670	5,740	5,770	91	100	99	74	84	86	49	61	67	34	46	51
Average				93	99	102	80	92	98	63	79	90	46	64	78
1 : 2 Mortar															
1	8,680	8,940	9,740	84	91	95	80	91	99	70	87	101	60	79	86
3	7,490	8,120	9,420	100	104	104	99	114	109	92	113	110	85	102	98
14	8,680	8,940	9,740	94	101	101	81	93	97	60	76	84	44	61	71
29	8,680	8,940	9,740	92	98	99	78	88	92	58	71	79	34	48	61
Average				92	98	100	84	96	99	70	87	94	56	72	79
1 : 3.5 Mortar															
1	4,140	4,050	4,270	87	103	105	76	98	103	66	90	110	57	80	103
3	4,140	4,050	4,270	92	101	105	87	108	116	72	103	125	66	99	119
14	4,140	4,050	4,270	90	99	96	78	91	99	53	72	87	37	57	80
29	3,890	4,090	4,160	93	96	98	75	86	90	55	68	80	36	49	65
Average				90	100	101	79	96	102	62	83	100	49	71	92

[1] Moist air storage at 73° F.
[2] Each value is an average of three 2-inch cubes.
[3] Reported as a percentage of the strength of control mortar.

the amount of water required for uniform consistency of cement-fly ash mortars was not constant. The effect of each fly ash on the water requirement of a 1:2.75 mortar is shown in figure 13, where the samples are arranged from left to right in increasing order of their carbon content. As stated before, the water requirement ratio is the amount of water used to prepare a mortar containing fly ash expressed as a percentage of the amount of water used to prepare the corresponding control mortar. The ratios plotted are average values for the 35-percent replacement mortars prepared with all three cements.

Some fly ashes which contained very little carbon improved the workability of the mortar to such an extent that less water was required for the mortar containing fly ash than for the control mortar. The quantities of water required for mortar of uniform consistency generally increased with the carbon content of the fly ash, although the departures from this trend indicate that differences in physical characteristics also affect the water requirement as would be expected.

The relation between the pozzolanic strength index and the water requirement ratio is shown in figure 14, and appears to be somewhat better than that obtained with either carbon content (fig. 12) or fineness as determined by the No. 325 sieve (fig. 11). This would appear to be logical, since both the carbon content and fineness of fly ash tend to affect the amount of water needed for a uniform consistency of mortar.

Relation of Chemical Constitution to Pozzolanic Strength Index

The pozzolanic strength indexes were plotted against the total amounts of each of the inorganic constituents previously given in table 1. These include alumina, iron oxide, calcium oxide, magnesium oxide, sulfur trioxide, alkalies as equivalent sodium oxide, and silica. No indication of a definite relation was found in any of these plots. Even though no relations were found, plots of pozzolanic strength index against total alkalies as Na_2O and silica are shown in figure 15 because of the general interest in these constituents.

Considering the general relation found between the alkali content of cement and mortar strength ratios at 28 days (table 9), it might be thought that the alkalies in the fly ash would be a significant factor. Figure 15 shows that those fly ashes with the highest alkali content had high pozzolanic strength indexes, but for most of the materials the strength index appears to be independent of the alkali content. The silica in fly ash is of interest, as it might be expected from the definition of a pozzolanic material that this constituent

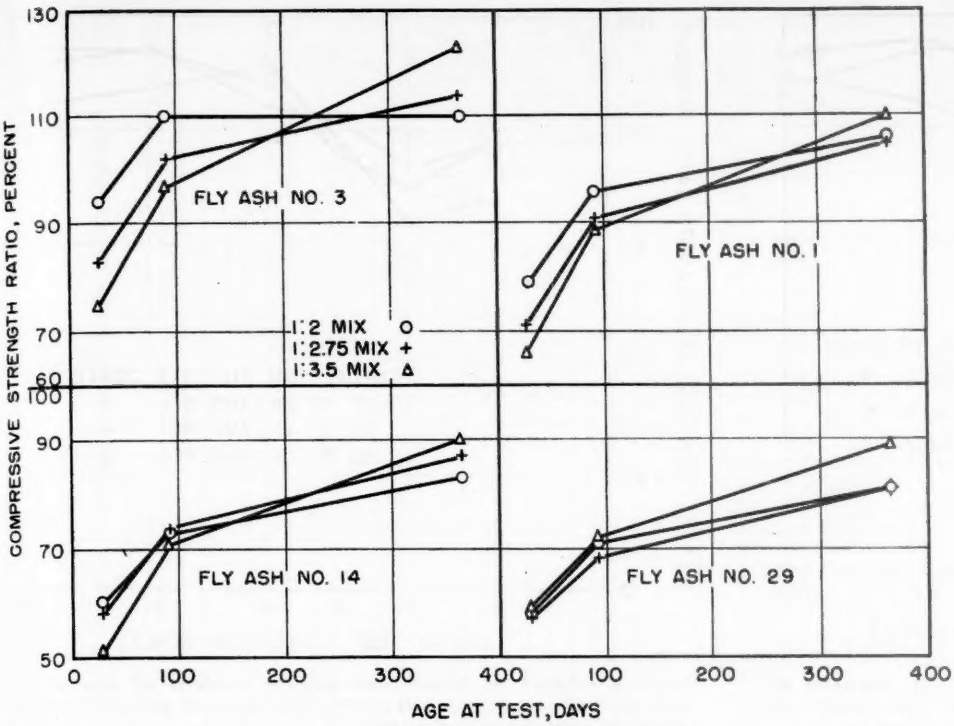

Figure 6.—Effect of mix proportions on strength of cement-fly ash mortar with 4 fly ashes used as replacement for 35 percent of the cement.

would have some effect on the strength of mortar. It is possible that silica may influence the strength of mortar to some extent, but the scattered pattern obtained in figure 15 shows that there is no direct relation that applies generally to all fly ashes.

Use of Fly Ash To Prevent Expansion by Alkali-Aggregate Reaction

A frequent cause of failure in concrete is the expansion and cracking that may result from the attack of certain reactive siliceous constituents of the aggregate by the alkalies in the cement. It has been found that the destructive effects of this reaction can be prevented by the addition to the concrete of a very finely divided siliceous material which is itself reactive with the alkalies in cement.

The effectiveness of 17 fly ashes in preventing or reducing the expansion resulting from the alkali-aggregate reaction was determined by measuring the change in length of 1- by 1- by 11¼-inch mortar bar specimens stored in moist air at 100° F. Control specimens were prepared from a basic reactive mortar consisting of a 1:2 mix by weight using graded Ottawa sand containing 2 percent of reactive opal passing the No. 8 and retained on the No. 50 sieve. Each fly ash was used to replace 10, 20, 35, or 50 percent of the cement on a solid volume basis. In all other respects the procedure outlined in the test for Potential Alkali Reactivity of Cement-Aggregate Combinations (ASTM Designation C 227–51 T) was followed. All cement-fly ash combinations with opal added were prepared with both cements A and B, which contained 0.90 and 0.13 percent equivalent Na_2O, respectively. In addition, specimens without opal were prepared with both cements and various percentages of each fly ash.

All specimens prepared either without opal or with the low-alkali cement showed expansions of less than 0.05 percent at an age of one year and are not reported here. The expansion of mortars containing opal and prepared with cement A (0.90 percent alkali) is shown in table 11 for ages of one month and one year. All specimens prepared with the same fly ash were made on the same day with a set of control specimens and were stored and tested together. Although the different sets of control specimens failed to develop the same amount of expansion, each set may be used to judge the effect of the single fly ash to which it applies.

It is evident that any of the fly ashes tested will prevent the expansion caused by the alkali-aggregate reaction if sufficient quantity is used. At an age of one year, for example, replacement of 35 or 50 percent of the cement by any of the fly ashes limited the change in volume to a maximum of 0.04 percent which is comparable with that shown by nonreactive mortars. All specimens have been measured to an age of 2 years, but no significant increase in volume has occurred in those having a replacement of 35 or 50 percent fly ash. Although a replacement of 20 percent of the cement by fly ash reduced the expansion at one year, it did not reduce it to a safe amount in all cases. The reduction effected by a 20-percent replacement varied considerably for different fly ashes, indicating that they are not equally effective in preventing the expansion resulting from the alkali-aggregate reaction. This difference in effectiveness is illustrated in figure 16, p. 136.

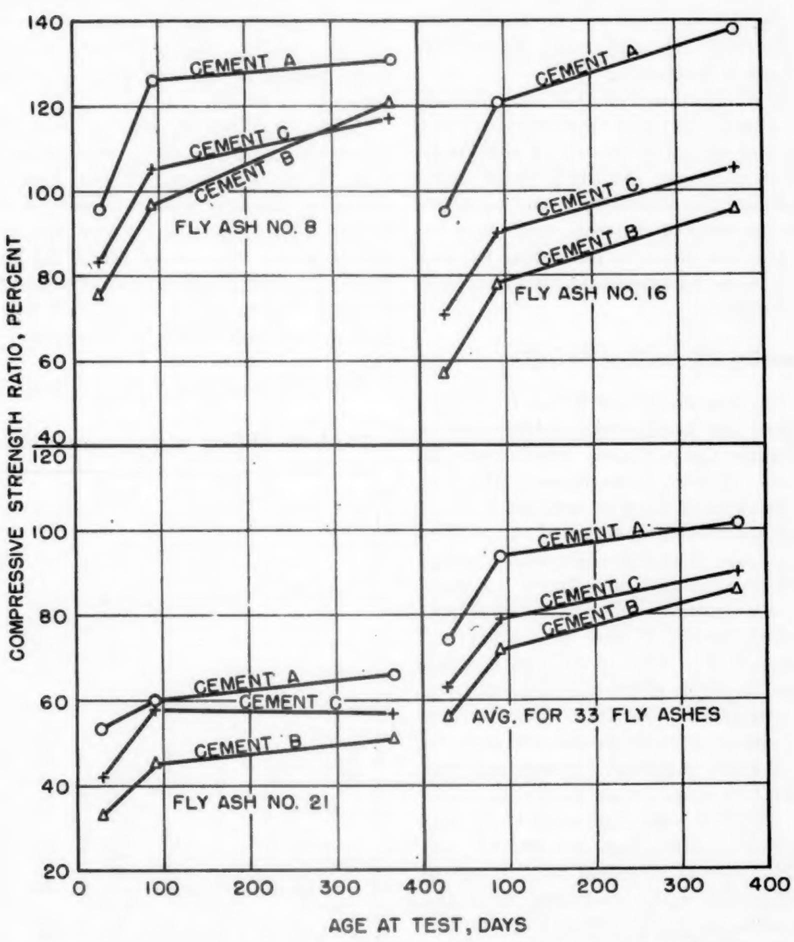

Figure 7.—Effect of cement on strength of cement-fly ash mortar (1:2.75 mix, 35-percent replacement of cement with fly ash).

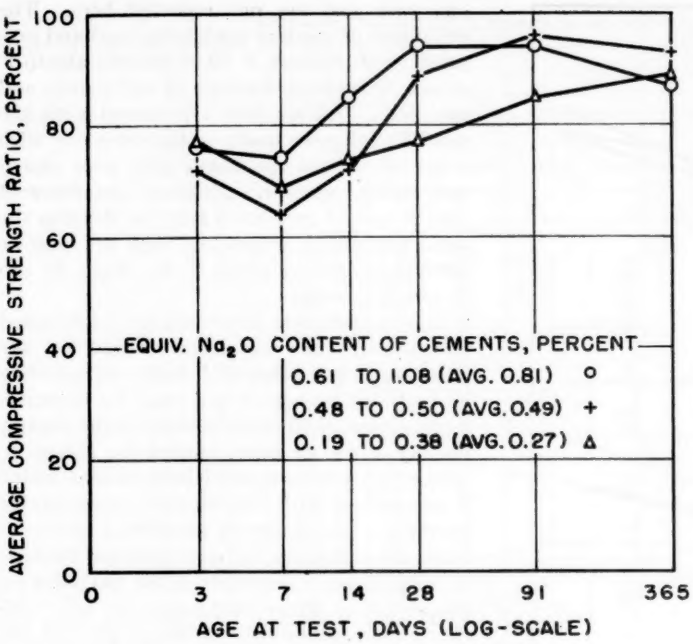

Figure 8.—Effect of alkali content of cement on strength of cement-fly ash mortar (1:2 mix, 50-percent replacement of cement with fly ash).

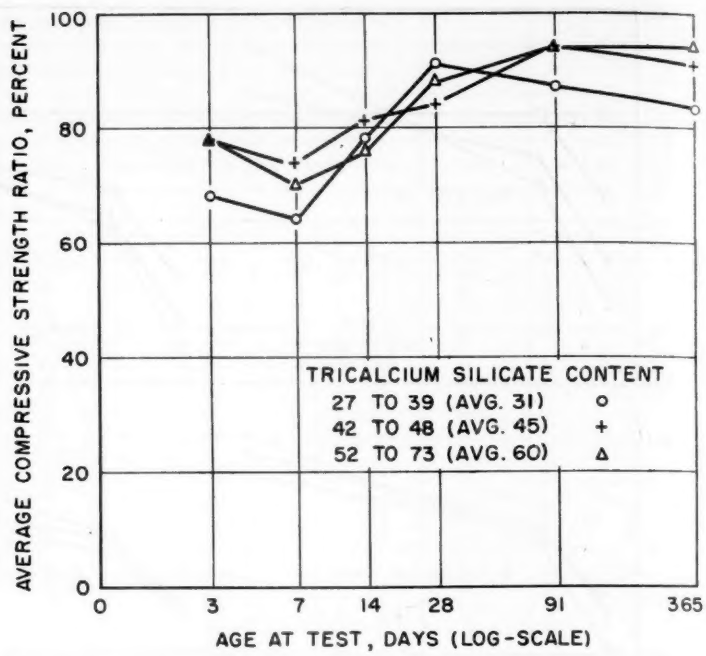

Figure 9.—Effect of tricalcium silicate content of cement on strength of cement-fly ash mortar (1:2 mix, 50-percent replacement of cement with fly ash).

For the particular reactive mortar used in these tests, a 10-percent replacement of cement with fly ash did not produce a substantial reduction in expansion, and in some cases, the change in volume was increased. At an age of one year, specimens prepared with 7 of the 17 fly ashes in the 10-percent replacement group showed more expansion than the control specimens.

It should be emphasized that the mortar tests upon which this discussion is based may not reflect the actual behavior of materials when used in concrete. At the present time, tests of mortar bars cannot be relied upon as substitutes for tests of concrete specimens to determine the amount of a particular fly ash which must be used to prevent expansion in a reactive concrete.

Special Chemical Studies

Since strength tests of mortar are time consuming, there has been considerable interest in the development of more rapid tests to measure the activity of pozzolans. Most of these tests have attempted to measure in some way special chemical properties of the pozzolans alone or the chemical changes occurring in mixtures of lime and pozzolans. In their paper on determining pozzolanic activity, Moran and Gilliland (*8*) give a summary of most of these tests. They point out in summation that "a single short-time test will not evaluate pozzolanic activity, particularly when any one of several properties may be desired in a given material. It appears that each material requires rather exhaustive testing, after which it may be possible to empirically relate a quick test for control purposes." The special chemical tests made in this investigation were conducted with the latter objective in mind. They were undertaken to supply a background of information for further work so that ultimately it might be possible to establish interrelations between various properties and test results which would make possible more rapid methods of test.

The special tests conducted on the fly ash itself involved chiefly the determination of constituents soluble in water or sodium hydroxide, and the changes in solubility resulting from reactions of lime and fly ash in the presence of water.

Table 12 shows the amount and calculated composition of the water soluble material in each of the fly ashes. These data were obtained by shaking a 5-gram sample of fly ash in 100 ml. of distilled water for one hour, allowing the mixture to stand 24 hours and filtering the supernatant liquid without further dilution or washing. The pH of this extract was determined and is also recorded in table 12.

Chemical analyses were conducted on aliquots for the amounts of calcium, sodium, potassium, and sulfate. The total amount of dissolved material was also determined by evaporating the water from an aliquot and drying the residue at 110° C. The composition of the dissolved salts was calculated by assuming that all of the sulfate was combined as gypsum ($CaSO_4 \cdot 2H_2O$). The balance of the calcium was then calculated as calcium hydroxide ($Ca(OH)_2$). The sodium and potassium were assumed to be present as the hydroxides (NaOH or KOH). Generally there is good agreement between the total amount of soluble material and the total amount of calculated salts. This is an indication of the validity of the assumptions made in calculating the composition.

The pH values of the extracts depend on the proportions of water and sample used in the test as well as the composition of the dissolved material, and there is no direct relation

Table 9.—Effect of cement on the compressive strength ratio of cement-fly ash mortar

Cement identification	Properties of cements				Compressive strength ratio of 1:2 mortars with 50-percent replacement of cement with fly ash No. 3 after—					
	Alkali content, equivalent Na_2O	Tricalcium silicate content	Fineness by turbidimeter	Compressive strength of 1:2 control mortar at 28 days	3 days	7 days	14 days	28 days	91 days	1 year
	Pct.	*Pct.*	*cm²/gm.*	*P. s. i.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
M	1.08	27	2,100	5,025	68	62	81	96	94	83
L	.82	48	1,860	6,365	83	87	95	94	97	89
K	.74	28	2,000	5,210	61	66	80	89	80	77
J	.61	52	1,800	6,600	90	81	85	98	104	100
Average	.81	39	1,940	5,800	76	74	85	94	94	87
I	.50	55	1,870	6,610	72	67	74	95	103	98
H	.48	73	2,440	8,540	69	62	71	85	99	92
G	.48	39	1,760	6,415	76	64	72	88	87	90
Average	.49	56	2,025	7,190	72	64	72	89	96	93
F	.38	42	1,860	7.950	81	68	71	74	92	85
E	.24	46	2,040	7,135	69	67	76	85	93	99
D	.19	61	1,780	8,125	81	72	76	72	70	84
Average	.27	50	1,890	7,740	77	69	74	77	85	89

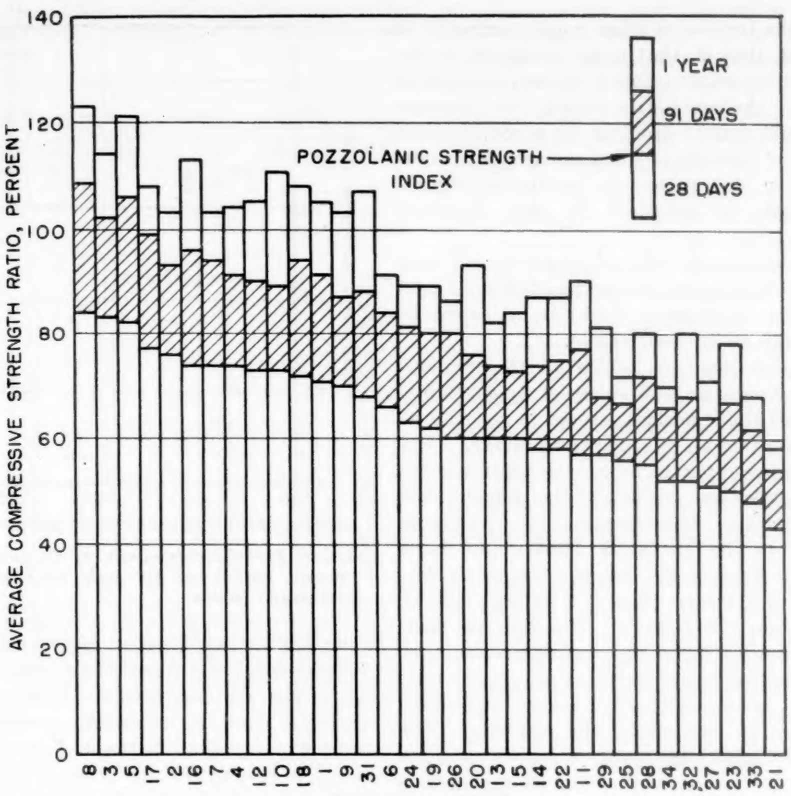

Figure 10.—Development of compressive strength in cement-fly ash mortar (1:2.75 mix, 35-percent replacement of cement with fly ash).

between the quantitative amount of any particular constituent and the pH. Generally the values obtained are those to be expected from a consideration of the calculated amount of calcium hydroxide present. In table 12, the pH value is relatively low for those extracts having no calcium hydroxide by calculation and high for those extracts in which the calculated calcium hydroxide is large. For all samples that have a calculated lime content greater than 2.0 percent, the pH of the extract was 12.0 or more.

The data for the soluble salts in table 12 show that essentially all of the extracted water soluble material is either calcium sulfate or calcium hydroxide, the relative amounts of each varying greatly for different fly ashes. These data, however, do not indicate the state in which the soluble materials are present in the original fly ash. The calcium sulfate may be present in any of its three forms—anhydrous, hemihydrate, or dihydrate—depending upon the conditions surrounding the fly ash during storage or handling. Likewise the calcium hydroxide may be present as uncombined lime or may have formed from the hydrolysis of lime-silica complexes after the addition of water.

To verify the presence of uncombined lime in the fly ash prior to wetting with water, determinations were made by the alcohol-glycerol method, such as is used in the determination of free lime in portland cement (ASTM Method C 114–53). The results of these tests are given in table 13. This table also includes the total amount of calcium that is present in the sample and the amount that is water soluble. The part of the water soluble calcium that is calcium hydroxide and the part that is calcium sulfate are also given. All these results are expressed in terms of an equivalent amount of calcium oxide to provide a common basis of comparison. It can be seen that for most of the samples the determined free lime is approximately the same as the calculated water soluble calcium hydroxide, thus indicating that the addition of water to fly ash does not result in the formation of calcium hydroxide by the hydrolysis of lime complexes. It will also be noted that a considerable portion of the calcium is not soluble in water, and therefore is probably present as a calcium glass.

The data in table 14 were obtained by making the test for reactivity of pozzolans with sodium hydroxide solution as described in Appendix A of the report by Moran and Gilliland on determining pozzolanic activity (*8*). This test is an adaptation of a procedure now designated as the Tentative Method of Test for Potential Reactivity of Aggregates (Chemical Method), ASTM Designation C 289–54 T. It involves treatment of the sample with 1 N. solution of sodium hydroxide in a sealed container at 80° C. for a 24-hour period. At the end of this period, the solution is filtered and the resulting filtrate examined. In the tests described by Moran and Gilliland, only the reduction in alkalinity (the amount of sodium hydroxide consumed by the reactions taking place) and the amount of silica dissolved were determined. In this investigation the amounts of alumina and sulfate dissolved were also determined.

This test was originally proposed for use on calcined shales. For this type of material it showed some promise in evaluating the ability of the pozzolan to prevent expansion resulting from the alkali-aggregate reaction. Consequently, consideration has been given to its application to fly ash. It was found however that the presence of calcium sulfate in a fly ash affects the results obtained by this test. When calcium sulfate dissolves, the calcium ion precipitates much of the silica which might normally be soluble and remain in solution if no calcium were present. The presence of dissolved calcium sulfate might also affect the reduction in alkalinity by causing a precipita-

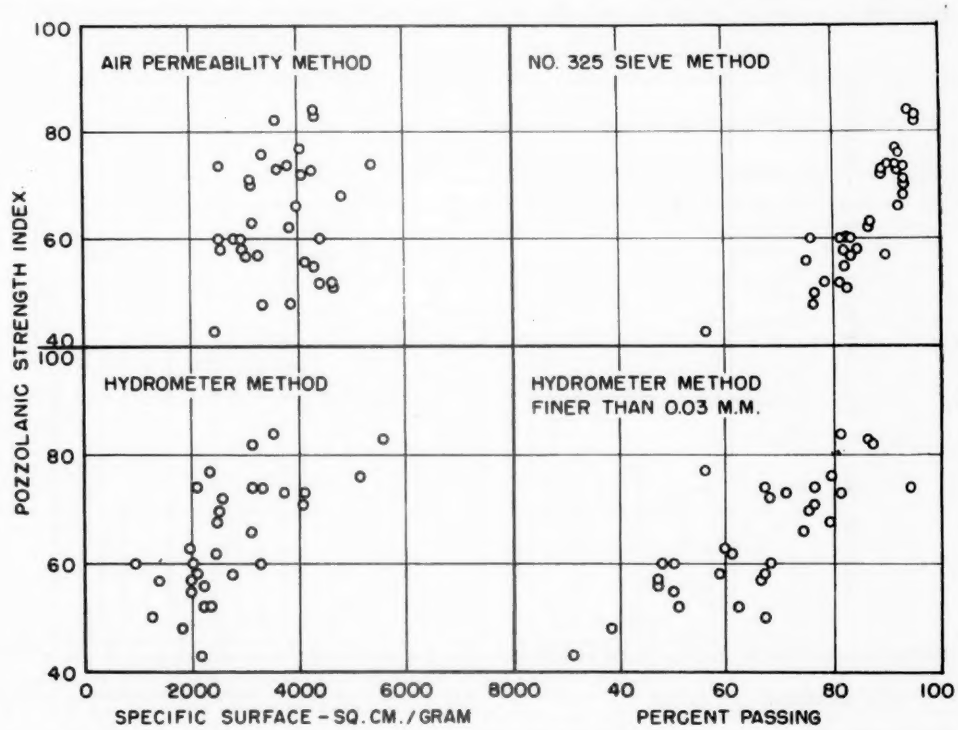

Figure 11.—Comparison of fineness of fly ash and pozzolanic strength index.

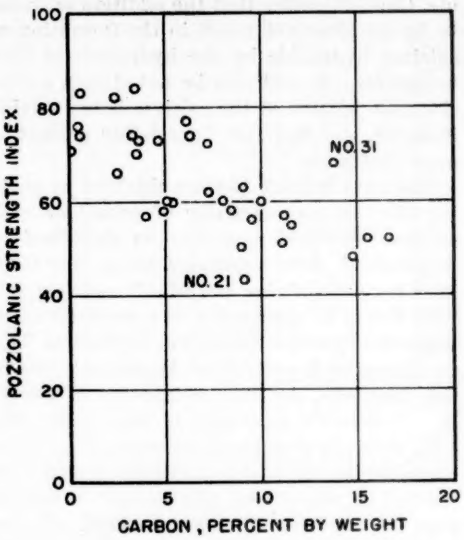

Figure 12.—Comparison of carbon content of fly ash and pozzolanic strength index.

tion of calcium hydroxide from solution. The data in table 13 illustrate these effects.

In most cases where the calcium sulfate dissolved is relatively high (as indicated by the amount of SO_3), the amount of silica dissolved is low and the reduction in alkalinity is relatively high. It appears that the relation between soluble silica and reduction in alkalinity is controlled by the amount of calcium sulfate present as well as by the characteristics of the siliceous material. Values for reduction in alkalinity and amount of silica dissolved which have been found suitable for acceptance requirements of other types of pozzolans may not be applicable to fly ashes.

A plot of the pozzolanic strength index against the reduction in alkalinity failed to show any correlation. An apparent relation between the strength developed and the silica dissolved is shown in figure 17, but this relation is the inverse of what might normally be expected, that is, that larger amounts of dissolved silica would result in greater pozzolanic activity. As previously stated, the presence of calcium sulfate controls to a considerable extent the amount of silica remaining in solution. For this reason no particular significance can be attached to this apparent relation.

The amount of Al_2O_3 dissolved varied from 0.03 to 0.41 percent, the median being 0.1 percent. No significance could be attached to the variations in these values.

The data given in tables 15–18 were obtained by analysis of a slurry of fly ash, lime, and water that had been stored in an oven at 100° F. for periods of 7, 28, and 91 days. The procedure used for the preparation and storage of the slurries was essentially the same as that given for the determination of "available alkalies" in the Tentative Methods of Sampling and Testing Fly Ash for Use as an Admixture in Portland Cement Concrete, ASTM Designation C 311–54 T. This test has been proposed as a relative measure of the amounts of alkalies from the fly ash that are made available for reaction with any reactive aggregate that may be present in the concrete. For this study tests were made on slurries at ages of 7 and 91 days as well as the 28 days called for in the ASTM method. Some variation in technique from the ASTM method was found necessary to insure better control of test conditions; the details of the test procedure used for this investigation are given in Appendix A (procedure 2).

Table 15 shows the individual amounts of sodium and potassium oxides that were extracted with water after each test period and the total of these two expressed as an equivalent amount of sodium oxide. Each result is expressed as a percentage of the total amount of the constituent present in each fly ash. The total amounts of alkalies present in each

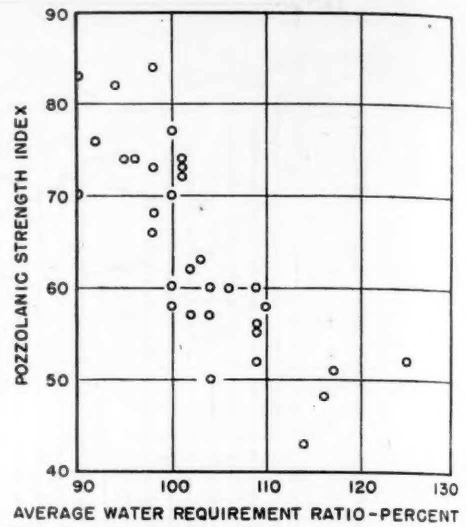

Figure 14.—Comparison of water requirement ratios of fly ash and pozzolanic strength index.

sample and the alkalies soluble at 28 days expressed as percentages of the original weight of fly ash are also given. These results invariably show considerable increase in the solubility of alkali between 7 and 28 days, but the results for the 91-day period differ with the samples tested. Some show little or no further increase, but others show a marked increase in the alkali dissolved. This increase was as much as 28 percent of the equivalent (total) alkali in the case of sample 23. The increase was greater than 10 percent in 18 of the 34 samples. It is evident that storage of lime-fly ash slurry for 28 days does not yield a result for soluble alkalies that can be related to the ultimate solubility of the alkalies in lime solution.

In order to obtain additional information of the chemical changes taking place in intimate mixtures of fly ash and lime in the presence of water, the residues after the extraction of the alkalies were digested in dilute hydrochloric acid (1:10). The acid solution was filtered off and the residue from this treatment digested in sodium hydroxide (1 percent). This was then filtered. Each of the filtrates thus obtained was examined for the amounts of silica, alumina, and iron oxide present. The details of the procedure used are described in Appendix A (procedure 2). These results are shown in tables 16–18, respectively.

Because of the exploratory nature of these tests, relatively large experimental errors are likely but the results are of interest because they show that the solubility of the alumina (table 17) was increased to a much greater extent during the period covered by the tests than was the solubility of the silica (table 16). Table 16 shows that for some samples there is a general trend toward larger amounts of acid-soluble silica being present for the longer period of storage, but the results are erratic. In all cases only a small fraction of the total amount of silica present was soluble in acid. The change with age in the acid solubility of the alumina shown in table 17 is considerable. The acid soluble alumina at 7 days is in the range of 2 to 4 percent for most samples, but

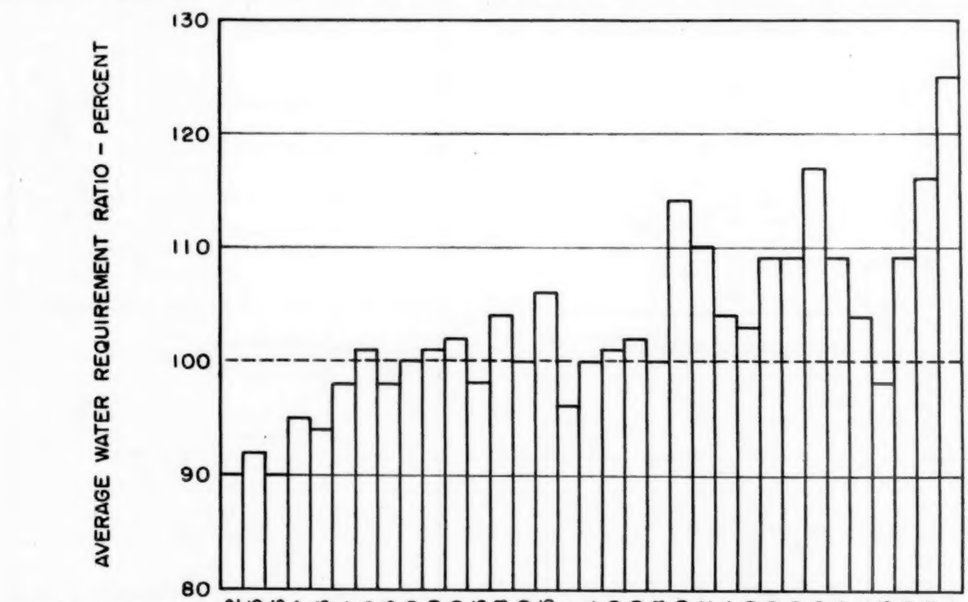

Figure 13.—Water requirement ratios in cement-fly ash mortar for 33 fly ashes (1:2.75 mix, 35-percent replacement of cement with fly ash).

Table 10.—Effect of carbon in fly ash on the compressive strength of cement-fly ash mortar

Fly ash number	Method of replacing cement with fly ash [1]	Carbon content of fly ash	Water requirement ratio, based on control mortar	Compressive strength ratio, based on 1:2.75 control mortar at— 28 days	91 days
		Percent	*Percent*	*Percent*	*Percent*
1	1	0.2	84	89	108
	2	.0	82	87	108
	3	.0	83	86	104
7	1	3.5	96	80	99
	2	.0	86	74	85
	3	.0	86	76	90
14	1	5.0	100	66	76
	2	.0	88	71	84
	3	.0	88	68	83
29	1	11.2	96	65	81
	2	.0	86	85	106
	3	.0	86	68	86
32	1	14.3	104	57	69
	2	.0	90	71	90
	3	.0	90	61	75

[1] In the three methods used, 35 percent of the solid volume of cement in the control mortar was replaced as follows: *Method 1*, by an equal volume of fly ash as received; *method 2*, by an equal volume of fly ash after ignition at 550° C.: and *method 3*, by an amount of ignited fly ash equal in volume to that of the inorganic portion of the fly ash used in method 1.

at 91 days this range is 7 to 10 percent. Generally, the increase in the solubility of the alumina between 7 and 91 days represented from 20 to 30 percent of the total alumina in the sample. The solubility of the iron oxide shown in table 18 indicates somewhat the same trend as that of the alumina but to a lesser degree.

Because of the considerable increase with time in the solubility of alumina in the presence of lime and water, the relation of this acid-soluble alumina to the pozzolanic strength index is of interest. Figure 18 shows the amount of acid-soluble alumina after 91 days plotted against the pozzolanic strength index. There is a general trend toward higher strength ratios for larger amounts of acid-soluble alumina, but it is also apparent that samples having widely different amounts of acid-soluble alumina have essentially the same strength index. Although the reactivity of the alumina may be a factor in the development of strength, other factors must exert a greater influence.

The amounts of alkali-soluble material shown in tables 16–18 have little significance. This alkali digestion was made primarily to determine whether significant changes occurred in the amount of amorphous silica present in the fly ash during reaction with lime. The test procedure was based on the assumption that only this form of silica would be insoluble in the acid treatment and soluble in the alkali solution. However, the glassy constituents of the fly ash were evidently decomposed to some extent by the conditions of the test and no definite trend could be established.

Lime-Fly Ash Tests for Measuring Pozzolanic Activity

The development of strength as a result of pozzolanic action requires that lime be available for reaction with the active constituent of a pozzolanic material. Some of the earliest methods of evaluating pozzolanic activity included determination of the effect of the reaction taking place in pozzolan-lime mixtures. Data obtained using three such procedures are shown in table 19.

In one method, lime-fly ash mortar was cured at temperatures of 100° and 130° F. and the compressive strength determined at an age of 7 days. Full details of this test as performed in this investigation are given in procedure 3 of Appendix A. Except for fly ash samples 1, 2, and 3, higher strengths were obtained by curing the specimens at 130° F. than at 100° F. The data show that the higher curing temperature is generally of marked benefit to the less active fly ashes. A comparison between the pozzolanic strength index and the compressive strength of lime-fly ash mortar cured at 100° F. failed to show any correlation. A reasonable relation between the index and the strength of the lime-fly ash mortar cured at 130° F. is shown in figure 19. However, the six fly ashes identified by number in figure 19 do not follow the general trend.

Alexander and Wardlaw (*9*) have indicated that lime mortar tests of pozzolanic materials conducted for a fixed period at constant temperature may not provide a proper measure of the reactivity of such materials. It is possible that fly ashes 4, 7, 8, 12, and 17 would have shown greater reactivity with lime if the test had been made under other conditions of storage such as higher temperature or longer curing.

The second method involved the determination of the time of setting of a lime-fly ash mixture. Moran and Gilliland (*8*) described this method as developed by Feret and used for evaluating pozzolanic materials other than

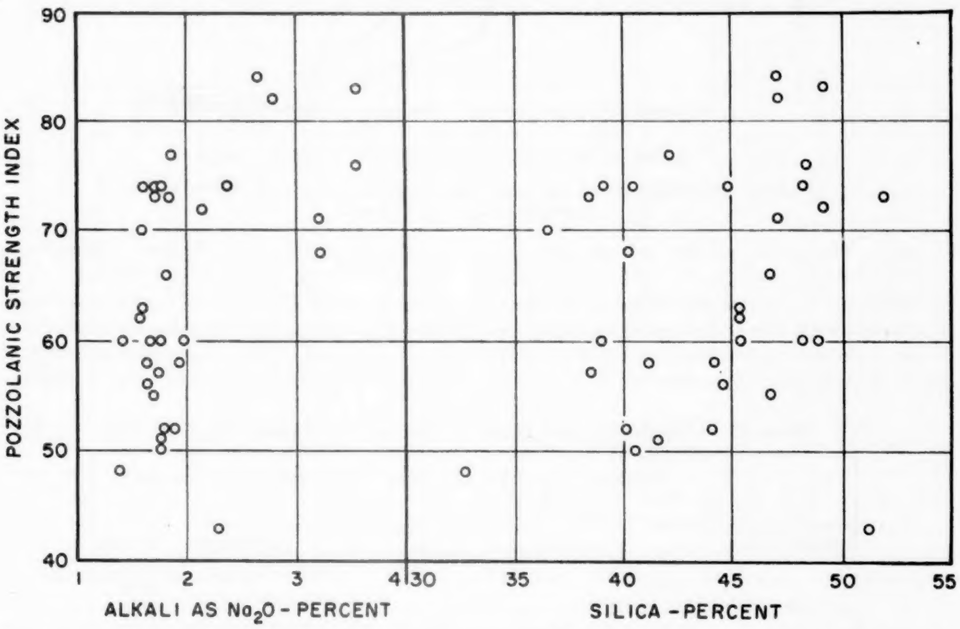

Figure 15.—Comparison of alkali or silica content of fly ash and pozzolanic strength index.

Table 11.—Effect of fly ash on the volume change of an alkali-reactive mortar containing opal

Fly ash number	Expansion of mortar bars with 0-50 percent replacement of cement with fly ash and stored at 100° F.[1] — Age of 1 month: None	10	20	35	50	Age of 1 year: None	10	20	35	50
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
4	0.10	0.03	0.02	0.00	0.01	0.62	0.54	0.19	0.01	0.00
5	.12	.07	.02	.00	.00	.53	.39	.09	.01	.01
6	.07	.04	.02	.02	.01	.38	.30	.17	.02	.01
7	.11	.12	.02	.01	.01	.46	.46	.18	.01	.01
8	.06	.12	.02	.01	.02	.41	.40	.11	.02	.02
9	.14	.12	.00	.01	.00	.52	.43	.09	.00	.00
10	.02	.03	.01	.00	.00	.44	.45	.15	.01	.00
11	.09	.08	.02	.02	.02	.39	.40	.12	.02	.01
12	.02	.04	.02	.00	.01	.56	.35	.04	.01	.02
13	.05	.10	.01	.00	.02	.63	.48	.20	.00	.02
15	.08	.05	.00	.00	.00	.50	.47	.17	.02	.01
16	.02	.07	.02	.01	.02	.54	.55	.27	.02	.03
19	.10	.06	.00	.00	.01	.43	.45	.13	.01	.02
25	.04	.12	.02	.02	.02	.40	.54	.25	.03	.02
27	.05	.10	.04	.02	.01	.44	.46	.39	.02	.01
28	.06	.10	.02	.00	.02	.38	.37	.08	.01	.01
34	.09	.10	.02	.01	.02	.45	.49	.30	.04	.01
Average	.07	.08	.02	.01	.01	.48	.44	.17	.02	.01

[1] Specimens prepared with cement A (equivalent Na_2O=0.90 percent). Each value is an average for two specimens.

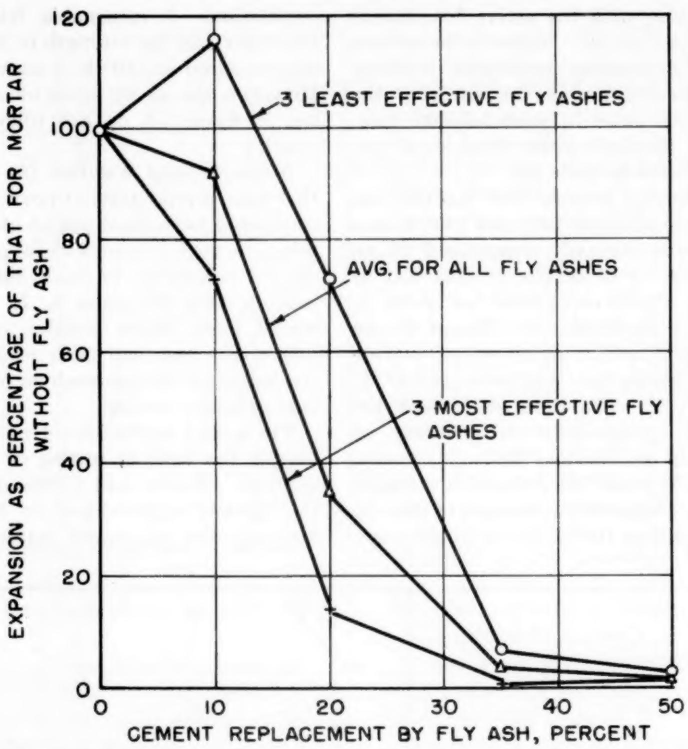

Figure 16.—Effect of fly ash on expansion of alkali-reactive mortar at age of 1 year.

Table 12.—Alkalinity and composition of water extracts of fly ash

Fly ash number	pH of extract	Calculated composition of dissolved material [1]				Total dissolved material [1]		
		$CaSO_4.2H_2O$	$Ca(OH)_2$	NaOH	KOH	Calculated	Determined (dried at 110° C.)	Difference (determined less calculated)
		Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	11.8	3.66	1.22	0.23	0.06	5.17	5.16	−0.01
2	11.7	3.02	.65	.34	.07	4.08	4.08	.00
3	11.7	4.41	.18	.45	.11	5.15	5.19	.04
4	11.8	2.02	1.43	.03	.06	3.54	3.49	−.05
5	11.8	2.87	1.00	.18	.06	4.11	3.93	−.18
6	11.8	3.12	1.44	.06	.06	4.68	4.55	−.13
7	11.0	2.18	.13	.05	.10	2.46	2.54	.08
8	11.7	1.75	.18	.08	.06	2.07	2.14	.07
9	12.0	1.59	2.02	.05	.02	3.68	4.48	.80
10	12.3	2.97	3.80	.04	.05	6.86	6.65	−.21
11	10.6	.95	.15	.03	.02	1.15	1.30	.15
12	11.3	.79	.33	.03	.02	1.17	1.30	.13
13	10.1	.47	.04	.01	.02	.54	.73	.19
14	12.0	1.13	1.25	.08	.02	2.48	2.94	.46
15	11.9	1.29	1.66	.04	.02	3.01	3.15	.14
16	12.3	2.68	4.48	.04	.02	7.22	7.15	−.07
17	11.4	1.84	.42	.05	.02	2.33	2.28	−.05
18	11.3	.97	.30	.04	.05	1.36	1.58	.22
19	9.9	.64	.03	.03	.04	.74	.77	.03
20	12.1	.40	2.59	.01	.02	3.02	3.92	.90
21	11.3	.47	.46	.03	.04	1.00	1.22	.22
22	12.3	1.46	3.74	.01	.02	5.23	5.31	.08
23	12.0	2.42	2.92	.04	.02	5.40	5.34	−.06
24	9.0	.65	.00	.04	.00	.69	.70	.01
25	10.4	1.54	.17	.01	.02	1.74	1.78	.04
26	8.5	.73	.00	.04	.05	.82	.78	−.04
27	12.0	3.19	2.30	.06	.06	5.61	5.45	−.16
28	9.3	.64	.00	.03	.02	.69	.75	.06
29	11.1	1.04	.41	.03	.01	1.49	1.62	.13
30	11.9	.89	.45	.08	.02	1.44	1.67	.23
31	11.0	4.35	.07	.34	.22	4.98	4.80	−.18
32	10.8	.43	.12	.03	.02	.60	.68	.08
33	10.0	2.81	.17	.03	.06	3.07	3.12	.05
34	11.2	3.03	.65	.03	.00	3.71	3.84	.13

[1] Expressed as a percentage of the original weight of fly ash.

Table 13.—The distribution of the calcium in fly ash

Fly ash number	Calcium [1] as CaO from—				
	Total sample	Total water-soluble	Water-soluble $CaSO_4$	Water-soluble $Ca(OH)_2$	Free lime [2]
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
1	7.0	2.1	1.2	0.9	0.9
2	5.2	1.5	1.0	.5	.5
3	5.5	1.6	1.4	.2	.0
4	5.2	1.7	.7	1.0	.9
5	5.2	1.7	.9	.8	.6
6	6.4	2.1	1.0	1.1	.8
7	1.7	.8	.7	.1	.2
8	4.5	.7	.6	.1	.5
9	7.8	2.0	.5	1.5	1.6
10	8.3	3.9	1.0	2.9	2.3
11	1.8	.4	.3	.1	.0
12	2.3	.5	.3	.2	.1
13	1.6	.2	.2	.0	.0
14	6.0	1.3	.4	.9	1.4
15	6.4	1.7	.4	1.3	1.0
16	11.6	4.3	.9	3.4	2.6
17	4.3	.9	.6	.3	.2
18	3.6	.5	.3	.2	.2
19	1.4	.2	.2	.0	.0
20	5.2	2.1	.1	2.0	1.5
21	1.6	.5	.1	.4	.3
22	7.6	3.3	.5	2.8	2.3
23	8.5	3.0	.8	2.2	1.6
24	1.5	.2	.2	.0	.0
25	6.2	.6	.5	.1	.0
26	1.2	.2	.2	.0	.0
27	6.8	2.8	1.0	1.8	1.0
28	1.1	.2	.2	.0	.0
29	3.2	.6	.3	.3	.1
30	12.0	.6	.3	.3	.9
31	3.9	1.5	1.4	.1	.0
32	1.7	.2	.1	.1	.0
33	1.8	1.0	.9	.1	.0
34	3.5	1.5	1.0	.5	.0

[1] Expressed as a percentage of the original weight of fly ash.
[2] Determined by ASTM Method C 114–53.

fly ash. The details of the test are given in procedure 4 of Appendix A. When the initial and final setting times shown in table 19 are compared with the pozzolanic strength indexes, a general trend towards an inverse relation is found, but the relation is not sufficiently definite to make the test of much value for determining the quality of fly ash.

Moran and Gilliland (*8*) also described a lime absorption test to measure the activity of a pozzolan. This test provides for the measurement of the amount of lime absorbed from a saturated lime solution over periods of time. The absorption of lime was measured by the decrease in the amount of acid required to neutralize an aliquot of the solution. The difference between the amounts absorbed at 7 and 28 days was then taken as a measure of the pozzolanic activity of the material. The details of the test as performed in this investigation are given in procedure 5 of Appendix A. Moran and Gilliland showed good correlation between the results of this test and the strength of portland cement-pozzolan mortars when the pozzolans were volcanic ash or pumice. The results obtained with this test on the fly ashes used in this investigation are shown in table 19.

A comparison of these results with the pozzolanic strength indexes failed to show any correlation. For a number of samples, negative values were obtained. This is not surprising as it was shown in the tests of lime-fly ash slurries that the alkalies in fly ash are slowly soluble in the presence of lime. Although the use of the 7-day result as the starting point would eliminate the effect of rapidly soluble constituents, the continued solubility of constituents in the fly ash after that time affects the equilibrium conditions with respect to lime and alkalies in solution. This test is considered not applicable to fly ashes.

Test Methods and Specification Requirements for Fly Ash

The determinations made on fly ash in this study generally follow procedures which have

been used previously for testing either fly ash or other types of pozzolans. The significance of each of these determinations for measuring the quality of fly ash has been assessed by comparison of the effects of fly ash on the strength of mortar. In the following discussion the test methods and specification requirements which are usually applied to fly ash are evaluated in view of the data obtained in this investigation.

The results of these tests indicate that the effect of fly ash on the strength of mortar is related to the carbon content of the fly ash, the fineness as determined by use of the No. 325 sieve or the 0.03 mm. size in the hydrometer analysis, and the water requirement ratio. The use of the No. 325 sieve is preferred over the hydrometer method for determination of fineness because of the relative simplicity of the method. Limiting values for these properties which were found for fly ashes having various degrees of pozzolanic activity are shown in table 20. This information can be used for making a quick evaluation of a fly ash in terms of its carbon content, loss on ignition, fineness, and water requirement ratio. The data in this table may also serve as a basis for preparing a specification for fly ash for use in concrete.

Although the data in table 20 indicate that fly ashes of a selected quality as measured by the strength index will generally meet certain limits for carbon content, loss on ignition, fineness, and water requirement ratio, it should not be inferred that limits on these properties alone will always insure a particular level of pozzolanic activity. Since the relations existing between pozzolanic activity and these properties are not exact, some fly ashes may not be as active as an appraisal based on these properties would indicate. Fly ash No. 6, for example, with a loss on ignition of 4.1 percent, 92.1 percent passing the No. 325 sieve, and a water requirement ratio of 98 percent, would be expected on the basis of table 20 to have a higher strength index than 66 as shown in figure 10. This shows that limits on these properties of fly ash do not eliminate the need for a more positive test for pozzolanic activity.

Specifications for fly ash generally include some requirement based on a test for strength of mortar prepared with cement or lime in combination with fly ash. When the mortar is prepared with lime, a minimum strength is usually specified. When cement is used, the strength of mortar containing fly ash is required to be equal to or greater than a definite percentage of the strength of a control mortar not containing fly ash. Any type I cement of acceptable quality is generally permitted in these tests.

It has been shown in this investigation that the strength ratio for a particular fly ash may vary considerably when determined with different cements. Consequently, when a minimum strength ratio is specified, consideration should be given to the cements to be used in the testing procedure. The most desirable procedure would be to use cement from a single source, or if this is not feasible, to use cements which have been found to produce comparable results in mortars containing fly ash. Further research on this problem is desirable to determine whether certain properties of cement can be used for selecting such cements. There is evidence, for example, that the alkali and tricalcium silicate contents of the cement may have an important bearing on its behavior with fly ash.

Table 14.—Reaction of fly ash with sodium hydroxide solution [1]

Fly ash number	Reduction in alkalinity of solution	Silicon dioxide [2] (SiO_2) dissolved	Aluminum oxide [2] (Al_2O_3) dissolved	Sulfur trioxide [2] (SO_3) dissolved
	Percent	*Percent*	*Percent*	*Percent*
1	42.6	0.45	0.10	2.38
2	36.7	.68	.10	1.92
3	42.1	.49	.10	2.48
4	33.8	.58	.11	1.33
5	37.2	.56	.11	1.66
6	46.1	.71	.06	1.92
7	29.3	1.39	.07	.93
8	30.0	.50	.14	1.10
9	37.5	.36	.17	1.21
10	45.2	.43	.10	2.09
11	28.7	2.59	.06	.47
12	27.3	.77	.13	.38
13	22.5	1.74	.08	.22
14	29.0	.51	.16	.80
15	33.8	.76	.09	.91
16	38.1	.26	.41	1.58
17	38.7	.27	.25	.95
18	23.9	.29	.34	.49
19	24.2	2.47	.06	.32
20	25.0	.72	.12	.27
21	22.2	2.26	.06	.22
22	35.7	.84	.08	.86
23	44.3	.76	.06	1.54
24	18.2	.58	.19	.30
25	41.4	.96	.05	.76
26	27.9	3.26	.05	.35
27	50.7	.66	.04	2.06
28	31.5	3.32	.05	.35
29	25.8	.48	.20	.50
30	28.7	1.04	.08	.70
31	31.8	.34	.19	2.02
32	18.2	.83	.14	.17
33	34.1	1.52	.06	1.31
34	44.9	1.33	.03	1.50

[1] Fly ash treated with 1 N. solution of sodium hydroxide for 24 hours at 80° C. in a sealed container. ASTM Method C 289-52T, except that a 12.5-gram sample was used.

[2] Expressed as a percentage of the original weight of fly ash.

Table 15.—Solubility of alkalies in water after various periods of aging fly ash and lime slurries

Fly ash number	Proportion [1] of sodium oxide soluble at—			Proportion [1] of potassium oxide soluble at—			Proportion [1] of equivalent alkalies as sodium oxide soluble at—			Equivalent alkalies as sodium oxide [2]	
	7 days	28 days	91 days	7 days	28 days	91 days	7 days	28 days	91 days	Total amount	Soluble at 28 days
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	18	42	42	12	34	40	15	38	41	3.21	1.23
2	19	35	46	12	30	42	16	33	44	3.55	1.16
3	25	43	41	13	33	37	20	39	39	3.55	1.38
4	14	29	31	12	37	57	12	35	52	1.61	.56
5	19	42	45	12	39	47	15	40	46	2.79	1.13
6	22	44	50	18	49	66	19	47	62	1.82	.86
7	20	40	40	14	48	59	15	46	55	1.78	.82
8	13	31	37	10	34	41	11	33	39	2.64	.88
9	15	45	55	10	42	61	12	44	58	1.59	.70
10	20	42	45	19	52	64	19	49	59	1.72	.85
11	12	42	35	10	48	52	10	46	48	1.72	.80
12	12	30	40	9	33	45	10	32	44	1.85	.60
13	14	36	59	9	41	54	10	40	55	1.40	.56
14	13	38	47	9	38	45	11	38	46	1.93	.74
15	13	45	68	10	45	70	12	45	69	1.67	.75
16	13	38	43	9	39	45	11	39	45	2.38	.92
17	12	24	48	15	44	53	14	37	51	1.87	.69
18	14	28	45	12	34	50	12	32	48	2.15	.69
19	8	36	56	9	46	66	9	44	64	1.57	.69
20	7	27	54	7	32	49	7	31	50	1.78	.55
21	8	27	37	8	37	46	8	35	44	2.29	.79
22	25	28	50	10	43	59	13	40	57	1.62	.64
23	13	33	60	9	36	65	11	35	63	1.77	.62
24	13	30	42	10	34	46	11	32	44	1.60	.52
25	16	34	47	20	47	56	19	45	54	1.64	.74
26	12	33	52	9	42	64	10	40	60	1.97	.78
27	21	48	48	22	60	63	22	56	59	1.76	.98
28	12	36	50	10	44	57	11	52	55	1.85	.97
29	30	38	62	7	25	39	15	29	47	1.84	.53
30	18	37	37	16	44	38	17	38	37	1.94	.74
31	24	46	55	12	37	48	16	41	50	3.11	1.26
32	9	34	41	8	36	48	8	35	46	1.79	.63
33	20	48	64	12	51	63	14	50	63	1.39	.70
34	14	46	54	13	51	59	13	49	58	1.88	.92

[1] Expressed as a percentage of the amount of the constituent present in the original fly ash sample (table 1, p. 122).

[2] Expressed as a percentage of the original weight of fly ash.

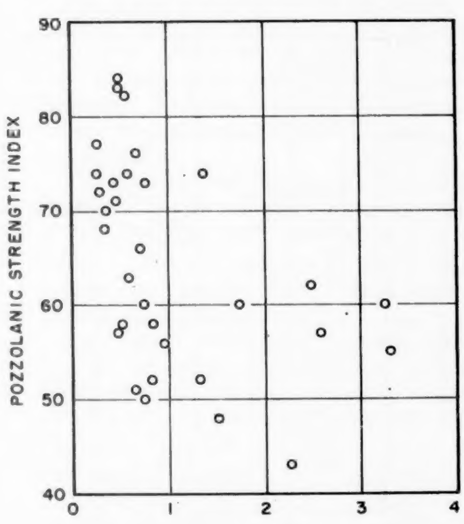

Figure 17.—Comparison of silica dissolved in NaOH solution and pozzolanic strength index.

Table 16.—Silica dissolved from fly ash after various periods of aging fly ash and lime slurries

Fly ash number	Acid soluble [1] at—			Alkali-acid soluble [2] at—		
	7 days	28 days	91 days	7 days	28 days	91 days
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	0.44	0.74	0.44	1.68	2.40	---
2	.41	.57	.41	2.03	1.56	---
3	.41	.73	.45	1.75	2.71	---
4	.29	.60	.35	.97	1.54	---
5	.37	.62	.38	1.77	1.60	---
6	.38	.63	.40	.71	1.93	---
7	.35	.55	.34	1.21	1.71	---
8	.32	.77	.39	2.07	2.38	---
9	.85	.47	.47	1.84	2.45	---
10	.40	.58	.44	1.38	1.69	---
11	.36	.68	.42	1.25	1.86	---
12	.41	.70	1.07	.72	2.59	0.92
13	.38	.67	1.03	.91	1.41	.97
14	.40	.73	.97	1.50	2.15	1.18
15	.40	.79	1.00	1.54	2.64	.95
16	.42	.64	.99	2.06	2.60	1.33
17	.39	.75	1.01	1.80	2.73	1.27
18	.41	.39	.64	1.78	2.57	1.14
19	.37	.30	.57	.74	2.46	1.31
20	.37	.34	.49	.87	2.26	1.10
21	.40	.30	.59	1.00	2.22	1.76
22	.34	.33	---	1.00	1.24	---
23	.40	.36	.63	.90	1.45	1.87
24	.44	.30	.57	1.11	1.32	.88
25	.44	.32	.53	1.53	1.85	1.32
26	.43	.33	.50	1.41	2.17	1.32
27	.38	.33	.53	1.38	1.97	1.19
28	.42	.32	.51	1.04	2.16	1.49
29	.44	.42	.51	1.63	1.96	.95
30	.46	.38	.42	1.73	1.82	1.25
31	.38	.29	.44	1.85	2.16	1.54
32	.46	.32	.49	.96	1.25	.98
33	.42	.30	.48	.85	1.53	.80
34	.41	.36	.43	1.08	2.05	1.11

[1] Amount dissolved by digesting the residue from water extraction in HCl (1:10) overnight. Expressed as a percentage of the original weight of fly ash.

[2] Amount dissolved by digesting the residue from the acid treatment for 30 minutes on steam bath in 1 percent NaOH solution. HCl added to make solution acid immediately before filtering. Results are expressed as percentages of the original weight of fly ash.

Table 17.—Alumina dissolved from fly ash after various periods of aging fly ash and lime slurries

Fly ash number	Acid soluble [1] at—			Alkali-acid soluble [2] at—		
	7 days	28 days	91 days	7 days	28 days	91 days
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	3.8	7.2	8.4	0.33	0.38	---
2	3.9	7.0	8.7	.36	.36	---
3	3.9	7.8	9.4	.48	.53	---
4	2.2	5.6	7.9	.46	.31	---
5	3.6	7.9	9.2	.38	.32	---
6	3.7	5.9	7.1	.19	.37	---
7	2.0	5.7	6.9	.28	.36	---
8	4.1	8.5	10.1	.51	.62	---
9	4.9	8.2	10.4	.44	.42	---
10	2.9	6.2	7.8	.29	.29	---
11	2.2	5.8	7.7	.26	.35	---
12	3.0	7.1	9.9	.32	.38	0.24
13	2.2	5.6	7.7	.19	.38	.25
14	4.1	7.5	9.5	.30	.36	.27
15	3.8	6.8	9.2	.19	.31	.21
16	5.2	9.4	11.0	.43	.44	.38
17	4.9	9.5	12.3	.51	.47	.36
18	4.9	9.9	13.0	.45	.53	.36
19	1.9	5.4	7.4	.12	.32	.23
20	1.9	5.1	8.2	.15	.25	.16
21	1.5	4.6	6.5	.18	.36	.32
22	2.1	5.3	---	.20	.16	---
23	2.1	4.8	7.4	.16	.21	.27
24	3.2	6.9	9.9	.36	.23	.25
25	3.7	6.1	7.6	.38	.31	.29
26	2.0	5.3	7.3	.35	.32	.31
27	2.7	6.0	7.2	.35	.28	.26
28	2.0	5.4	7.4	.20	.28	.31
29	4.0	7.5	11.2	.44	.44	.32
30	3.6	5.0	5.5	.15	.15	.20
31	3.6	7.2	9.5	.45	.41	.38
32	2.3	5.7	8.2	.19	.19	.21
33	2.0	5.3	7.8	.21	.21	.11
34	3.0	6.2	7.9	.32	.27	.19

[1] Amount dissolved by digesting the residue from water extraction in HCl (1:10) overnight. Expressed as a percentage of the original weight of fly ash.

[2] Amount dissolved by digesting the residue from the acid treatment for 30 minutes on steam bath in 1 percent NaOH solution. HCl added to make solution acid immediately before filtering. Results are expressed as percentages of the original weight of fly ash.

Table 18.—Iron oxide dissolved from fly ash after various periods of aging fly ash and lime slurries

Fly ash number	Acid soluble [1] at—			Alkali-acid soluble [2] at—		
	7 days	28 days	91 days	7 days	28 days	91 days
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	1.5	2.4	2.9	0.09	0.09	---
2	1.6	2.5	3.2	.08	.12	---
3	2.1	3.1	3.7	.13	.16	---
4	1.2	2.1	2.6	.05	.10	---
5	1.5	2.8	3.6	.10	.09	---
6	.9	1.6	1.9	.04	.10	---
7	.8	1.7	2.3	.06	.12	---
8	1.8	3.1	3.9	.15	.23	---
9	1.8	2.3	3.2	.10	.17	---
10	1.1	2.0	2.7	.07	.10	---
11	.7	1.6	2.3	.06	.09	---
12	.8	1.7	2.4	.08	.10	0.08
13	.6	1.3	2.0	.07	.10	.13
14	1.3	1.7	2.8	.07	.12	.17
15	1.1	1.6	2.6	.04	.10	.15
16	2.2	3.2	3.9	.09	.16	.21
17	2.0	3.2	4.5	.16	.16	.17
18	1.4	1.9	2.5	.07	.10	.08
19	.7	1.6	2.3	.06	.10	.14
20	1.4	2.7	4.3	.09	.14	.12
21	.6	1.2	1.5	.06	.09	.08
22	1.4	2.5	---	.10	.08	---
23	1.0	1.6	2.1	.06	.06	.37
24	.8	1.7	2.4	.09	.07	.11
25	1.3	2.1	2.8	.12	.12	.15
26	.7	1.7	2.7	.09	.08	.15
27	1.0	1.8	2.1	.15	.12	.17
28	.6	1.5	2.1	.07	.07	.15
29	1.0	1.9	2.0	.09	.10	.12
30	1.9	2.1	2.3	.06	.07	.11
31	1.8	2.9	3.9	.12	.16	.24
32	.7	1.6	3.8	.07	.08	.14
33	1.0	2.0	2.4	.15	.17	.20
34	1.0	1.8	2.6	.17	.21	.21

[1] Amount dissolved by digesting the residue from water extraction in HCl (1:10) overnight. Expressed as a percentage of the original weight of fly ash.

[2] Amount dissolved by digesting the residue from the acid treatment for 30 minutes on steam bath in 1 percent NaOH solution. HCl added to make solution acid immediately before filtering. Results are expressed as percentages of the original weight of fly ash.

The minimum strength ratio or pozzolanic strength index which should be specified depends on factors not considered in this study. The pozzolanic strength indexes of four fly ashes used in this series representing sources of fly ash which have given good results in concrete vary from 71 to 83. The feasibility of using fly ashes of poorer quality will depend on such factors as the permissible reduction which can be tolerated in the 28-day strength of the concrete and the quality of fly ashes available in a particular locality.

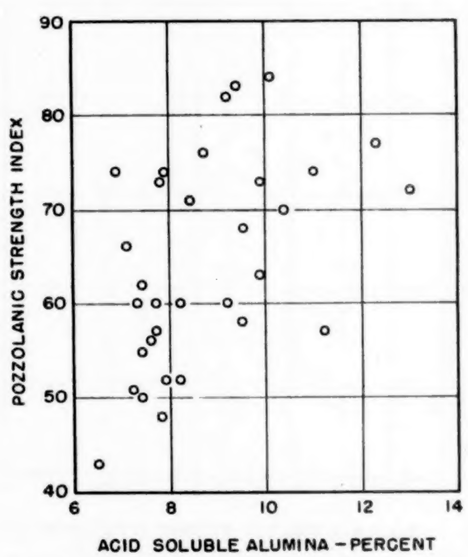

Figure 18.—Comparison of acid-soluble alumina after storage in lime solution for 91 days and pozzolanic strength index.

In the use of a lime-fly ash mortar for determining the pozzolanic activity of fly ash, control of the uniformity of the lime does not appear to be difficult. However, the results of the tests of fly ash with lime did not show as close a correlation with those in which cement was used as might be desired. This may have been due to the particular procedure followed in preparing the lime-fly ash mortars, and further work with this method may furnish better results.

At present the fineness of fly ash is usually specified in terms of specific surface determined by the air permeability method. The results given in this study show that specific surface so determined has no relation to the effect of fly ash on the strength of mortar. This is in contrast to the good correlation found with the amount passing the No. 325 sieve. The use of this sieve as a means for determining the fineness of fly ash appears to be desirable.

Except for carbon, the variations in the total amounts of individual chemical constituents that are present in the samples tested in this investigation had little or no relation to the pozzolanic activity of the fly ash. This does not necessarily mean that chemical constitution is not of importance, but rather that the normal variation in composition of the different fly ashes is not sufficient to produce significant changes in pozzolanic activity. It is likely that availability for reaction or the physical state of the constituents control the activity of a fly ash to a much greater extent

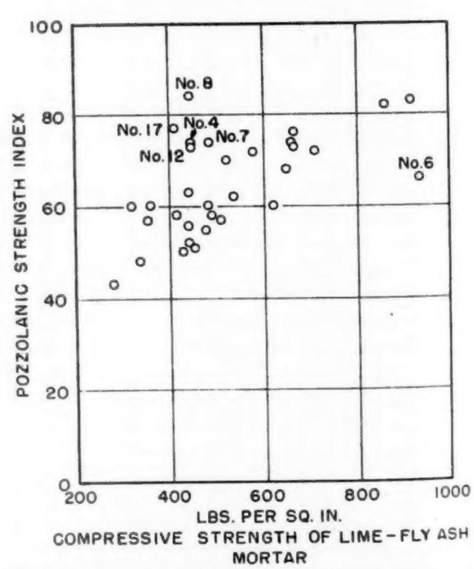

Figure 19.—Comparison of compressive strength of lime-fly ash mortar cured at 130° F. and pozzolanic strength index.

Table 19.—Results of lime-fly ash tests for pozzolanic activity

Fly ash number	Compressive strength at 7 days of 1:2:9 lime-fly ash mortar cured at—		Time of setting of 1:4 lime-fly ash mixture		Lime absorption at 28 days less that at 7 days, CaO per 100 grams of fly ash
	100° F.	130° F.	Initial	Final	
	P. s. i.	*P. s. i.*	*Hours*	*Hours*	*Grams*
1	670	580	140	313	2.25
2	785	670	141	195	1.39
3	925	920	52	120	1.98
4	175	445	234	258	.90
5	545	360	167	192	2.17
6	445	935	235	322	3.11
7	325	485	177	266	.60
8	385	445	90	168	−.23
9	175	520	120	195	.20
10	490	665	216	340	3.97
11	115	510	119	293	−.03
12	195	445	118	315	2.31
13	95	320	340	384	−.17
14	160	490	141	374	.32
15	115	485	142	194	1.49
16	235	660	119	143	1.96
17	105	410	72	651	−.04
18	160	710	166	450	.05
19	65	535	507	555	.00
20	65	360	187	404	----------
21	80	280	260	527	1.68
22	105	415	165	395	.86
23	135	425	315	482	1.75
24	100	440	170	315	−.01
25	210	440	139	420	3.47
26	125	620	339	651	.09
27	275	455	355	479	6.06
28	130	480	216	384	1.80
29	105	355	118	315	−.17
31	515	650	180	215	.01
32	110	440	340	501	−.28
33	55	335	259	404	−.16
34	175	440	381	673	2.83

than the total amount of constituent present. For this reason specification requirements for chemical constituents other than carbon are necessary only to limit potentially deleterious constituents or to eliminate freak materials. For fly ash, these requirements are generally limited to the percentages of silica, magnesia, sulfur trioxide, and in special cases available alkalies.

The ASTM Specification for fly ash (C 350–54 T) includes a minimum requirement for silica of 40 percent. Of the fly ashes examined in this investigation, six would fail to meet this requirement. Three of these six have pozzolanic strength indexes greater than 70 percent and appear satisfactory for use as admixtures in concrete. In view of this, it is believed that a slightly lower minimum silica content may be tolerated. A value of 35 percent is suggested as being suitable.

Limits for magnesia and sulfur trioxide are often included in a fly ash specification as a protection against possible deleterious effects in the concrete or mortar. This limit is usually 3 percent in each case. The maximum magnesium content found in any fly ash examined was 2.7 percent for sample 30, which was discarded for use in the mortar tests because of its coarseness and general unsuitability for use. The remaining samples showed a maximum value of 1.4 percent. Although a retention of the limit on magnesia to prevent the inclusion of unusual materials is believed necessary, these results indicate that the magnesia content for most fly ashes is well below this limit. The sulfur trioxide content, a measure of the amount of sulfates present, varied from 0.2 to 2.8 percent in the samples tested. A limit of 3 percent for this material appears to be suitable.

The alkalies present in a fly ash must be considered whenever the material is used in concrete in which there is a possibility that reactive aggregate may be present. The ASTM specification for fly ash (C 350–54 T) includes an optional clause which limits the available alkalies to 1.5 percent. As previously stated, these available alkalies are determined on a lime-fly ash slurry after storage at 100° F. for 28 days. All of the fly ashes included in this investigation meet this requirement, the largest amount of available alkalies being 1.38 percent for sample 3. However, it was also shown that in many cases the alkalies continued to dissolve after the 28-day period. It is believed that additional studies should be made to show the correlation between the results of this test and the amounts of alkalies becoming soluble in an actual mortar or concrete, and whether this continued solubility is of significance to the expansion resulting from the alkali-aggregate reaction.

Table 20.—Relation between limiting values of pozzolanic strength index and other properties of fly ashes

Number of fly ashes meeting indicated limits	Pozzolanic strength index, minimum	Carbon content, maximum	Loss on ignition, maximum	Amount passing No. 325 sieve, minimum	Average water requirement ratio, 35-percent replacement, maximum
		Percent	*Percent*	*Percent*	*Percent*
3	82	3.5	4.1	93.9	98
5	76	6.4	6.9	91.5	100
13	70	6.9	7.5	88.9	101
15	66	13.6	14.8	88.9	101
21	60	13.6	14.8	75.8	109
27	55	13.6	14.8	74.8	110
31	50	15.6	18.0	74.8	125
33	43	15.6	18.0	56.2	125

Appendix A

The following are general descriptions or details of testing procedures used in this investigation which may be of interest to those actively engaged in making similar studies.

Procedure 1

Methods of chemical analysis.—The oxide analyses, except for the alkalies, were conducted following the general methods outlined by Hillebrand, Lundell, Bright, and Hoffman (*10*) using a sodium carbonate fusion. The alkalies were determined by means of a flame photometer using the method described by Halstead and Chaiken (*11*).

Carbon was determined by weighing the CO_2 formed by ignition of the sample at 950° C. in a tube combustion furnace using oxygen. The total CO_2 absorbed was corrected for the amount resulting from carbonates by determining the CO_2 released by hydrochloric acid in a separate determination.

The sulfates (as SO_3) were determined in a portion of the sample dissolved in HCl(1:1) after 15–20 minutes digestion at a near boiling temperature.

Procedure 2

Preparation and analysis of lime-fly ash slurries.—The slurries were prepared as directed in the method for the determination of available alkalies as given in the Tentative Methods of Sampling and Testing Fly Ash for Use as an Admixture in Portland Cement Concrete, ASTM Designation C 311–54 T.

The extraction of the water soluble alkalies and the analyses of the residues were conducted as follows:

The liquid contents of the vial were transferred to a 250-ml. beaker and the solid cake transferred to a mortar. The cake was ground with the addition of some water until a uniform slurry was formed and no large lumps remained. The slurry was then transferred to the same 250-ml. beaker and sufficient water added to make the total volume 100 ml.

For most samples after 28 and 91 days, the solid cakes were so hard that the vial had to be broken and the glass carefully removed before grinding. The glass was scraped as thoroughly as possible to remove the adhering fly ash and lime.

After standing for 2 hours at room temperature with frequent stirring, the slurry was filtered and the residue washed thoroughly with hot water (8–10 times).

The filtrate was neutralized with HCl using 1 drop of phenolphthalein as indicator. It was then transferred to a 250-ml. volumetric flask and filled to the mark. This solution (or aliquot where necessary) was used to determine the amounts of sodium and potassium present by means of a flame photometer.

The flame photometer was calibrated with neutral solutions of sodium and potassium chlorides. The necessary correction for lime was made by determining the average amount present in several representative samples and using a correction curve established on that basis.

The residue from the water extraction was returned to the 250-ml. beaker and 13 ml. of concentrated HCl and 87 ml. of H_2O added. This amount was calculated to give a final concentration of free HCl equivalent to a dilution ratio of 1:10.

The beaker and its contents were allowed to stand overnight after frequent stirring for the first several hours. The liquid was filtered into a 250-ml. flask and the residue washed thoroughly with hot water. After the liquid had cooled, the flask was filled to the mark and aliquots of this solution were used for the determination of the acid soluble constituents.

The residue from the acid treatment was transferred to the 250-ml. beaker, and 100 ml. of hot 1-percent solution of sodium hydroxide added. It was then digested on a

steam bath for 20 minutes. Five ml. of concentrated HCl were added to make the solution slightly acid and to dissolve any iron hydroxide or aluminum hydroxide which may have been released from glassy complexes by the alkali treatment.

The solution was filtered into a 250-ml. volumetric flask, and the residue washed thoroughly with hot water. After the filtrate had cooled the flask was filled to the mark and aliquots of this solution were used for the determination of the constituents soluble in or "solubilized" by the alkali treatment.

Photometric methods were used to determine the amounts of dissolved constituents in each solution. Silica was determined by the molybdenum blue method, and iron and aluminum oxides were determined with ferron. The procedures followed were essentially the same as described by Shapiro and Brannock (*12*), except for necessary modifications to adjust for acid concentration.

Procedure 3

Compressive strength of lime-fly ash specimens.—The lime-fly ash mortar used for these specimens contained by weight one part hydrated lime, two parts fly ash, and nine parts of graded Ottawa sand. Sufficient water was added to this mixture to produce a flow of 80 plus or minus 5 percent when determined as prescribed in the Standard Method of Test for Compressive Strength of Hydraulic Cement Mortars, AASHO Designation T 106–49. The materials were mixed by hand in a 6-quart bowl. Sufficient mortar was prepared to fill two 1⅞-inch diameter cylindrical glass tubes, 12 inches in length, which had previously been sealed at the bottom. These tubes were filled in 6 equal layers, each layer being tamped 25 times with a metal tamper having a plane face one inch in diameter.

Immediately after molding, the specimens were sealed on the top with a rosin-paraffin mixture. After storage at 73° F. for 24 hours, one specimen was stored for 6 days at 100° F. and one was stored at 130° F. Three hours before testing at 7 days, each specimen was cut into three equal cylinders, the glass stripped, and the cylinders capped with a sulfur capping compound. The capped specimens were kept in a moist condition at 73° F. until tested in compression.

Procedure 4

Time of setting of lime-fly ash specimens.—A paste consisting of one part of hydrated lime and four parts of fly ash by weight was prepared with sufficient water to produce a paste of normal consistency as determined by the Method of Test for Normal Consistency of Hydraulic Cement, ASTM Designation C 187–49. This paste was placed in a cylindrical container of about 3-inch diameter, and covered with a layer of saturated lime water, which in turn was covered with a film of lubricating oil to prevent carbonization.

At intermittent intervals, the paste was tested by means of the Vicat needle to determine when initial and final set occurred. Initial set was considered to have occurred when the 1-mm. needle penetrated to 35 mm. from the upper surface of the paste in 30 seconds. When the needle showed no penetration of the surface of the paste, final set was considered to have taken place.

Procedure 5

Lime absorption test.—This test is intended to determine the capacity of a fly ash for reacting with lime in a lime water solution. The following procedure was used:

A 1-gram sample of fly ash was placed in a test tube to which was added 100 ml. of a lime water solution of known concentration as determined by titration with a standardized N/25 hydrochloric acid solution. The test tube was sealed and agitated constantly by mechanical means until the date of test. At ages of 7 and 28 days, a 25-ml. portion of the supernatant liquid was removed and immediately titrated with the N/25 hydrochloric acid solution. After the sample for test at an age of 7 days had been taken, the solution in the test tube was replenished with 25 ml. of lime water of the concentration originally used.

The amount of lime absorbed by the fly ash was determined by the change in alkalinity of the solution during each period of agitation, as indicated by the amount of N/25 hydrochloric acid needed for titration.

Appendix B

The following discussion[5] is based on a number of published references, and while there is not always complete agreement on all details, it is believed that it represents generally the consensus of thought concerning the chemical constitution of the inorganic matter in coal and the changes which occur during combustion to form fly ash.

The bulk of the inorganic material in coal is derived from detrital or adventitious matter which fills the fissures and cracks occurring in coal beds. This material consists mainly of silicates, sulfides, and carbonates. The siliceous matter is mostly shale and clay, kaolin being the most abundant mineral present. Smaller amounts of potash clays, micas, feldspars, and quartz may also be present. The shales are largely complex alumino-silicates in combination with small amounts of iron, calcium, sodium, and potassium. The sulfide minerals present are essentially in the form of pyrite (FeS_2) and marcasite (FeS_2). Calcite ($CaCO_3$) and siderite ($FeCO_3$) make up the bulk of the carbonate minerals occurring in coal beds. It has been estimated that more than 90 percent of the mineral matter in coal consists of kaolin, calcite, pyrite, and clay.

The grinding of pulverized fuel largely separates the coal from the associated minerals and even the minerals from each other into discrete particles. As the particles are burned in an air suspension, collisions are infrequent and the minerals are not again mixed. Thus, their residues appear separately in the fly ash.

When bituminous coals are used as the pulverized fuel, the small particles of coal in suspension are heated rapidly. The particles soften and swell into multicellular bubbles of coke, known as "cenospheres." Some particles of bituminous coal may increase in volume by as much as 40 times shortly after entering the furnace, the average being about 11 times the original volume. The density of coal (1.3 to 1.7) is thereby decreased to approximately 0.12 to 0.15 by cenosphere formation. Much of the inorganic matter in coal is finely divided. The swelling of the coal further separates and subdivides the ash into minute particles. As the cenospheres burn, numerous bits of mineral ash are released.

The mineral matter undergoes considerable decomposition and chemical change during combustion, and the chemical nature of the ash is quite different from that of the original mineral matter in coal.

Each of the three main minerals—kaolin, calcite, and pyrite—break down to their respective oxides at the temperature of the fuel bed (980–1650° C.), but the resulting oxides usually have melting points above the combustion temperature. However, eutectic relationships are formed which result in fusion.

In the flame, the shale and clay particles lose combined water and those particles which leave the flame prematurely do not complete the processes of fusion or that of moisture evolution. These particles are white and rounded, the whiteness being due to cavities formerly occupied by steam. The particles which continue in the flame tend to complete both processes, particularly in relatively hot combustion chambers, and they form mostly complex silicates that are colorless, solid spheres resembling glass. Various tints of color may be due to iron components in the shale. Some crystalline aluminum silicate (mullite) is also found.

The pyrite (FeS_2) is ignited to the oxide state with the accompanying evolution of sulfur dioxide (SO_2) and sulfur trioxide (SO_3). If the temperature is below 1,000° C., ferric oxide (Fe_2O_3) forms. However, the most likely situation is that ferroso-ferric oxide or magnetite (Fe_3O_4) is formed, since temperatures usually exceed 1,000° C. This material is in the form of black, rounded or spherical particles which are often mistaken for particles of carbon. The magnetite particles can be identified by their magnetic properties.

The calcite, of course, breaks down to calcium oxide and carbon dioxide during ignition. Usually the bulk of free lime so produced combines with the sulfur dioxide and trioxide evolved from the pyrite to form calcium sulfate. Generally, the sulfur oxides are fixed as sulfates by any free particles of basic oxides. Free lime not so converted to sulfates will remain as calcium oxide or be converted to calcium hydroxide during storage.

The unburned coal particles which rise to the stack will be found in the fly ash as large, gritty, porous, irregularly shaped particles of cindery coke.

[5] This discussion was prepared by Bernard Chaiken, Chemist, Physical Research Branch, Bureau of Public Roads.

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New Publication

A new publication entitled *Standard Plans for Highway Bridge Superstructures* (1956 edition) is now available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at $1.75 per copy.

The 52-page book comprises 18 series of standard plans which furnish details for a variety of types of highway bridge superstructures. Entirely new in this edition are three series for pretensioned precast concrete and five series for structural timber. From the previous (1953) edition, with revised and modernized designs, are series for I-beams, riveted or welded plate girders, reinforced concrete slabs, T-beams, and box girders, precast concrete decks, and post-tensioned precast concrete I-sections.

The plans will serve as a useful guide to State, county, and local highway departments in the development of suitable and economical bridge designs for primary, secondary, and urban highways. The drawings give sufficiently complete information so that they approach contract drawings as nearly as practicable.

The designs are based on two widths of roadway: 24 feet with H15–44 live load and 28 feet with H20–S16–44 live load. The ranges in span lengths, from 11 feet for structural timber to 140 for deck plate girder, are based on the economy and suitability of each particular type of superstructure.

Use of Fly Ash in Concrete

BY THE PHYSICAL RESEARCH BRANCH
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The purpose of this investigation was to study the properties of concrete containing, as replacement for part of the cement, four fly ashes selected from two widely separated areas because they represented sources of fly ash which have a history of extensive use in concrete. From each source, fly ashes of widely different fineness were selected with the expectation that those with the maximum fineness would have the lowest carbon content. Concrete specimens containing the fly ashes were tested for strength at various ages, for shrinkage at various periods when stored in a dry atmosphere, for durability in freezing and thawing, and for resistance to attack by calcium chloride used for ice removal.

These tests indicate, in general, that at ages through 28 days both flexural and compressive strengths were lower than comparable concrete without fly ash. At one year the strengths of the concrete containing fly ash were about as high or higher than the plain concrete. Fly ash did not improve the resistance to freezing and thawing of non-air-entrained concrete. In air-entrained concrete some of the fly ashes gave satisfactory durability and some did not. The particular portland cement used was also a factor. For the most part, concrete containing fly ash showed less shrinkage upon drying than concrete without fly ash. All substitutions of fly ash for portland cement adversely affected the resistance of both air-entrained and non-air-entrained concrete to attack by calcium chloride solutions.

IN an effort to develop a more durable concrete, research engineers have been seeking a low-cost form of finely divided silica for adding to portland cement concrete, which would react with the alkalies and lime liberated by the cement in the hydration process. A material which appears to have the desired properties is fly ash. This is a waste product which results from the burning of pulverized coal and accumulates in large quantities at power plants. It has a high silica content and a fineness similar to cement.

Not only have claims been made concerning the suitability of fly ash for producing a more durable concrete, but the product has been proposed as an extender or replacement for portland cement. Impetus has been given to the use of fly ash for this purpose because of the shortage of cement during the past few years.

In this study, the properties of concrete containing four fly ashes used as a substitute for cement were investigated.

Conclusions

Tests in which fly ash was used as a replacement for part of the cement indicated the importance of the carbon content of the fly ash. In general, the higher the amount of carbon in the fly ash and the greater the percentage of fly ash used as a replacement for cement, the lower was the compressive and flexural strength at all ages.

The detailed conclusions are as follows:

1. The 7-day compressive strengths of concretes containing fly ash were lower than comparable concrete without fly ash. With a few exceptions, the same relation was found for the 28-day strengths. The lower strengths were always obtained with the concretes containing the fly ashes of highest carbon content. At 1 year the strength of the concrete containing fly ash of low carbon content was always higher than that of the concrete without fly ash, in some cases as much as 20 percent higher; and the strength of the concretes containing 16⅔ percent of fly ashes X and Y (high carbon content) equaled or exceeded those without fly ash. Only the concretes containing 33⅓ percent of fly ashes X and Y failed to meet or surpass the strengths of the control concrete at 1 year.

2. Much the same general relations hold for flexural strength as were obtained for compressive strength, except that at 1 year the flexural strength of all concrete with fly ash replacement was greater than that of concrete without fly ash.

3. Non-air-entrained concrete with and without fly ash had poor resistance to freezing and thawing.

4. Satisfactory durability was obtained with the air-entrained concretes containing cements A and B without fly ash. For air-entrained mixes, similar results were found for the concretes containing cement B (low alkali content) and the various fly ash replacements. Satisfactory durability was also obtained with the concretes containing cement A (high alkali content) and the 16⅔-percent replacement of the four fly ashes and the 33⅓-percent replacement of fly ashes A and B; concrete with 33⅓-percent replacement of cement with fly ashes X and Y (high carbon content) had poor durability as indicated by factors of 40 or lower.

5. The effect on durability and strength of concrete containing fly ash from a given source varies with the characteristics of the cement used. Therefore, cement-fly ash combinations for which no service record is available should be investigated prior to use.

6. In general, there was little difference in the shrinkage upon drying of the concrete made with or without fly-ash substitutions.

7. Non-air-entrained concrete with or without fly ash was severely attacked by calcium chloride used for ice removal. The two air-entrained concretes without fly ash had good resistance to attack by calcium chloride, but all substitutions of fly ash for portland cement lowered the resistance of the concrete.

8. The amount of air-entraining material necessary to produce a given amount of air in concrete increases with the carbon content of the fly ash.

Scope of Tests and Materials Used

The fly ashes [2] from one area are identified hereafter as A and B, and from the other area as X and Y. From each source, fly ashes of widely different fineness were selected.

In this investigation specimens for compressive and flexural strength, durability, and volume change tests were made from concretes without air and with 3 to 6 percent entrained air. Since fly ash is generally used as a replacement for part of the portland cement in paving or structural concrete, it seemed logical that the air content should be maintained within the usual limits of 3 to 6 percent.

In order to investigate the possibility of reaction of the fly ash with the alkalies in the cement, two portland cements were used: one of relatively high and the other of relatively low alkali content. The chemical analyses of the two portland cements shown in table 1 indicate that cement A had an alkali content of 1.09 percent which is higher than that permitted by AASHO specification M 85–53 for a low alkali cement, and that cement B had a very low alkali content, 0.14 percent.

Each of the four fly ashes was used as a replacement for portland cement in two percentages (16⅔ and 33⅓) for strength determinations and freezing and thawing and volume change measurements. For the concrete slabs which were stored outdoors and exposed

[1] This article was presented at the 59th Annual Meeting of the American Society for Testing Materials, Atlantic City, N. J., June 17–22, 1956.

[2] Fly ashes A, B, X, and Y are identified as 1, 3, 14, and 29, respectively, in the article *Studies relating to the testing of fly ash for use in concrete*, which appears in this issue.

to the action of calcium chloride, only a 33⅓-percent replacement was used. In each case the replacement of cement by fly ash was on the basis of solid volumes.

Concrete for compressive and flexural strength test specimens was made with 1½-inch maximum size crushed limestone and a siliceous sand with a fineness modulus of 2.75. The aggregates were of good quality and had a good service record for durability. Aggregates from the same sources were used in making the volume change and freezing and thawing specimens and the outdoor exposure slabs, except that the maximum size was limited to 1 inch. This maximum size was required because of the small size specimens.

Mix Proportions

The mix data for all concrete specimens are given in table 2. Mixes without fly ash were designed for a cement content of 6.0 sacks of cement per cubic yard and a slump of approximately 3.0 inches. Where fly ash was used, one or two sacks of cement per cubic yard of concrete were replaced by an equal solid volume of fly ash. Because of differences in specific gravities of the cements and the fly ashes, the weight of fly ash for a solid volume equivalent to the solid volume of a 94-pound sack of cement was 74 pounds for fly ashes A, B, and X, and 72 pounds for fly ash Y. The quantity of sand in air-entrained mixes was reduced to compensate for the volume of added air, thus maintaining a constant cement content. For all mixes with the same maximum size coarse aggregate, the actual weight of coarse aggregate per cubic yard of concrete was constant.

The water requirement for concrete of a given slump varied with the amount and properties of the fly ash used for replacement of cement. The mix data for the strength-test specimens shown in table 2 indicate that when 16⅔ percent of fly ash A or B was used, the water was approximately 1¼ gallons per cubic yard of concrete less than that in the mixes without fly ash; and when 33⅓ percent of fly ash A or B was used, the reduction was approximately 2¼ gallons per cubic yard. When either 16⅔ or 33⅓ percent of fly ash X was used, the water requirement was the same as for concrete without fly ash, but when 16⅔ percent of fly ash Y was used, approximately ½ gallon more water was required. In the case of fly ash Y with 33⅓ percent replacement, approximately 1 gallon more water was needed. The same trends were noted for the concrete used in the freezing and thawing and volume change tests.

The quantity of air-entraining admixture required for a constant air content increased with a higher carbon content in the fly ash and with the quantity of fly ash used as a replacement for the portland cement. This variation is shown in table 2. When either 16⅔ or 33⅓ percent of fly ash A was used, approximately 10 percent less air-entraining agent was required than was needed for the concrete with 100 percent portland cement. Also when 33⅓ percent of fly ash Y was used with cement B, approximately 5 times as much air-entraining admixture was required. Slump and air

Table 1.—Chemical composition and physical properties of portland cements and fly ashes

	Portland cement		Fly ash			
	A	B	A	B	X	Y
Chemical composition (in percent):						
Silicon dioxide	22.0	22.3	47.1	49.2	41.2	38.5
Aluminum oxide	5.6	5.4	18.2	19.9	22.1	23.5
Ferric oxide	2.5	2.4	19.2	16.2	20.6	18.8
Calcium oxide	62.8	66.1	7.0	5.5	6.0	3.2
Magnesium oxide	3.0	1.0	1.1	1.4	1.2	1.0
Sulfur trioxide	2.0	1.7	2.8	2.7	.9	.6
Loss on ignition	.8	1.2	[1] 1.2	[1] 1.2	[1] 5.4	[1] 11.6
Sodium oxide	.40	.04	1.80	2.00	1.00	.60
Potassium oxide	1.05	.15	2.15	2.35	1.42	1.88
Total equivalent alkalies as Na_2O	1.09	.14	3.21	3.55	1.93	1.84
Insoluble residue	.16	.12	--------	--------	--------	--------
Chloroform-soluble organic substances	.009	.003	--------	--------	--------	--------
Free calcium oxide	.85	.56	--------	--------	--------	--------
Water-soluble alkali:						
Na_2O	.11	.01	--------	--------	--------	--------
K_2O	.63	.02	--------	--------	--------	--------
Computed compound composition (in percent):						
Tricalcium silicate	42	55	--------	--------	--------	--------
Dicalcium silicate	31	22	--------	--------	--------	--------
Tricalcium aluminate	11	10	--------	--------	--------	--------
Tetracalcium aluminoferrite	8	7	--------	--------	--------	--------
Calcium sulfate	3.4	2.9	--------	--------	--------	--------
Carbon	--------	--------	.2	.6	5.0	11.2
Carbon dioxide	--------	--------	.01	.04	.04	.03
Physical properties:						
Apparent specific gravity	3.20	3.17	2.49	2.52	2.51	2.43
Specific surface (Wagner) cm.²/g.	1,800	1,625	--------	--------	--------	--------
Specific surface (Blaine) cm.²/g.	--------	--------	3,075	4,305	2,565	3,220
Passing No. 325 sieve percent	--------	--------	93.2	95.2	84.5	89.4
Autoclave expansion do	.32	.04	--------	--------	--------	--------
Normal consistency do	25.5	25.0	--------	--------	--------	--------
Time of setting (Gillmore test):						
Initial hours	3.2	4.2	--------	--------	--------	--------
Final do	5.2	6.4	--------	--------	--------	--------
Compressive strength (1:2.75 mortar):						
At 7 days p. s. i.	2,340	2,960	--------	--------	--------	--------
At 28 days do	3,670	5,070	--------	--------	--------	--------
Mortar air content percent	9.1	6.8	--------	--------	--------	--------

[1] Determination made at 600° C.

content were maintained approximately constant for all concretes.

Fabrication of Specimens

All mixing was done in an open pan-type mixer of 1¾ cubic foot capacity. The following mixing cycle was employed: Cement plus the fly ash and damp sand were mixed for 30 seconds, after which the estimated total quantity of mixing water plus the air-entraining admixture, if any, was added and the mortar mixed for a further period of 1 minute; coarse aggregate in a saturated surface-dry condition was then added and the concrete mixed for an additional 2 minutes, making a total mixing time of 3½ minutes. Air contents for the air-entrained concrete were determined by the pressure method, ASTM C 231–49 T, and for the non-air-entrained concrete it was calculated by the gravimetric method, ASTM C 138–44. Consistency was controlled by means of the slump test.

Testing Procedures

Strength specimens were molded, cured, and tested in accordance with applicable ASTM procedures. All strength specimens were moist cured continuously until tested.

The freezing and thawing tests were made on prisms 3 by 4 by 16 inches, sawed from 4- by 16- by 24-inch slabs. The concrete slabs were cured in the moist room for 14 days, stored in laboratory air for 7 days, and then sawed into 7 prisms measuring 3 by 4 by 16 inches. Three were used for the freezing and thawing test and the other four were held in moist air storage for future tests. The freezing and thawing prisms were returned to the moist room for 7 days, then immersed in water for 7 days, and at a total age of 35 days the freezing and thawing cycle was started.

A 24-hour cycle was used in making the freezing and thawing tests. Each specimen was frozen and thawed in water in an individual metal container of such size as to provide about ⅛-inch clearance on all sides. The specimens in the containers were placed vertically in the freezing chamber. The refrigerant used was alcohol and it entirely surrounded the sides of the container to a height of about 18 inches. The specimens in the containers were frozen at −10° F. for 18 hours, then removed from the freezer and thawed in a water bath at 70° F. for 6 hours. After each cycle, the specimens were removed from the containers, turned upside down, and replaced. The water in the containers was changed.

Resistance to the effects of alternate freezing and thawing was determined periodically during the test by measuring changes in the dynamic modulus of elasticity of the concrete. For a given specimen, changes in dynamic modulus of elasticity E are proportional to changes in the square of the natural frequency of vibration (N^2). It is therefore possible to use the reduction in N^2 directly as a measure of the deterioration of the concrete. Freezing and thawing was continued until the specimens showed a loss in N^2 of 40 percent or for 200 cycles, whichever occurred first.

In addition to the 4- by 16- by 24-inch slabs which were sawed for the freezing and thawing prisms, six 3- by 4- by 16-inch beams were made for volume change tests. These specimens were removed from the molds after 24 hours under moist burlap and then stored in laboratory air at 72° F. and 50 percent relative humidity. After 180 days in laboratory

Table 2.—Concrete mix data

Fly ash			Mixes for strength tests [2]							Mixes for freezing and thawing and volume change tests [5]					
Identification	Source	Amount of replacement [1]	Cement	Fly ash	Water	Slump	Weight of plastic concrete	Air [3]	Admixture [4]	Cement	Fly ash	Water	Slump	Weight of plastic concrete	Air [3]
PORTLAND CEMENT A: NON-AIR-ENTRAINED CONCRETE															
		Percent	*Sack/cu. yd.*	*Lb./cu. yd.*	*Gal./cu. yd.*	*Inches*	*Lb./cu. ft.*	*Percent*	*Percent*	*Sack/cu. yd.*	*Lb./cu. yd.*	*Gal./cu. yd.*	*Inches*	*Lb./cu. ft.*	*Percent*
None	--------	------	6.0	--------	33.7	3.0	151.6	1.6	------	5.9	--------	35.5	2.7	148.6	2.0
A	Midwest	16.7	5.0	74	32.9	3.1	151.6	1.5	------	5.0	74	33.0	2.5	149.1	2.8
A	do	33.3	4.1	148	31.0	2.6	151.4	1.7	------	4.0	148	34.2	2.5	148.9	1.4
B	do	16.7	5.1	74	31.8	2.6	152.0	1.5	------	5.0	74	34.8	2.4	149.4	1.3
B	do	33.3	4.1	148	31.1	2.7	152.1	1.3	------	4.0	148	35.1	3.3	149.3	.8
X	East	16.7	5.0	74	33.5	3.1	151.4	1.4	------	5.0	74	35.6	3.0	149.6	1.0
X	do	33.3	4.0	148	33.7	3.2	150.9	1.2	------	4.0	148	35.0	4.0	148.4	1.5
Y	do	16.7	5.0	72	33.6	2.7	151.2	1.4	------	4.9	72	36.1	3.5	148.6	1.4
Y	do	33.3	4.0	144	34.2	3.2	150.2	1.4	------	4.0	144	35.2	3.7	147.7	1.7
PORTLAND CEMENT A: AIR-ENTRAINED CONCRETE															
None	--------	------	6.0	--------	30.4	3.0	147.3	4.6	100	5.8	--------	31.9	3.0	141.2	6.6
A	Midwest	16.7	5.0	74	29.4	3.0	146.6	4.9	93	4.8	74	31.4	3.5	141.0	6.2
A	do	33.3	4.1	148	28.7	3.2	146.6	4.7	87	4.0	148	31.3	3.0	144.1	4.5
B	do	16.7	5.0	74	29.2	3.0	146.4	4.8	137	5.0	74	31.0	3.0	145.0	4.2
B	do	33.3	4.1	148	28.8	3.1	147.5	4.3	152	4.0	148	31.9	3.0	145.1	3.9
X	East	16.7	5.0	74	30.5	2.9	146.7	4.3	155	4.9	74	32.8	3.3	143.0	5.0
X	do	33.3	4.0	148	30.8	3.2	146.2	4.2	217	4.0	148	34.8	3.0	144.4	4.0
Y	do	16.7	5.0	72	31.0	2.8	145.5	4.8	242	4.8	72	34.5	4.0	141.6	5.8
Y	do	33.3	4.0	144	32.2	3.3	144.7	4.4	395	4.0	144	36.0	3.5	144.7	3.1
PORTLAND CEMENT B: NON-AIR-ENTRAINED CONCRETE															
None	--------	------	6.0	--------	34.8	3.0	151.6	1.3	------	5.9	--------	36.9	3.2	149.2	1.3
A	Midwest	16.7	5.0	74	33.3	3.1	151.4	1.4	------	4.9	74	36.9	3.0	149.3	.7
A	do	33.3	4.0	148	31.9	3.1	151.2	1.6	------	4.0	148	35.6	3.5	149.2	.7
B	do	16.7	5.0	74	32.8	2.9	151.6	1.5	------	4.9	74	35.8	3.5	148.9	1.3
B	do	33.3	4.0	148	31.6	3.0	151.6	1.6	------	4.0	148	34.3	3.5	149.2	1.1
X	East	16.7	5.0	74	34.6	3.5	150.9	1.3	------	4.9	74	37.2	3.0	148.5	1.1
X	do	33.3	4.0	148	34.5	3.5	150.5	1.2	------	4.0	148	37.0	3.2	148.4	.8
Y	do	16.7	5.0	72	34.7	3.2	150.8	1.3	------	4.9	72	36.3	2.7	148.6	1.3
Y	do	33.3	4.0	144	35.1	2.7	149.7	1.4	------	3.9	144	36.6	3.0	147.2	1.6
PORTLAND CEMENT B: AIR-ENTRAINED CONCRETE															
None	--------	------	6.0	--------	31.6	2.7	146.0	4.6	100	5.9	--------	32.7	2.8	143.4	5.4
A	Midwest	16.7	5.0	74	30.9	3.1	146.4	4.4	89	4.9	74	32.8	3.5	144.1	4.9
A	do	33.3	4.0	148	29.5	3.2	146.0	4.8	93	3.9	148	30.5	3.2	142.4	5.6
B	do	16.7	5.0	74	30.5	3.0	146.2	4.5	143	4.9	74	31.8	3.0	143.9	4.7
B	do	33.3	4.1	148	29.5	3.1	146.5	4.4	179	4.0	148	30.6	3.0	142.8	5.2
X	East	16.7	5.0	74	31.5	3.1	145.1	4.9	189	4.8	74	33.3	3.0	141.8	5.6
X	do	33.3	4.0	148	31.5	3.5	144.4	4.8	261	3.9	148	34.0	4.3	140.7	5.6
Y	do	16.7	5.0	72	32.5	3.1	146.4	4.2	279	4.9	72	35.0	3.3	144.1	3.1
Y	do	33.3	4.0	144	33.1	3.7	144.8	4.3	489	3.9	144	35.1	4.0	143.7	3.7

[1] Fly ash used as replacement for cement on a solid volume basis.
[2] Proportions for mixes without fly ash were as follows: For non-air-entrained concrete, 94-190-350; for air-entrained concrete, 94-170-350. Maximum size coarse aggregate, 1½ inches.
[3] Air contents for non-air-entrained concrete were calculated, whereas air contents for air-entrained concrete were determined by pressure method (ASTM method C 231-49 T).
[4] Relative amount of air-entraining admixture used to produce air in concrete for strength tests; amount used in mixes without fly ash considered as 100 percent.
[5] Proportions for mixes without fly ash were as follows: For non-air-entrained concrete, 94-205-330; for air-entrained concrete, 94-188-330. Maximum size coarse aggregate, 1 inch.

air, they were stored in water for 14 days and then returned to laboratory air for an additional 180 days. The length of each specimen was determined when it was taken out of the mold and periodically thereafter.

Additional 4- by 16- by 24-inch slabs were made later to determine the effect of fly ash on the resistance of concrete to scaling due to freezing and ice removal with calcium chloride. A raised edge was cast around the perimeter of each slab. In these tests only concretes containing 33⅓-percent replacement of each of the four fly ashes for both cements were used with the non-air-entrained and the air-entrained mixes. The slabs were cast in June 1952 and were stored in moist air for 30 days. They were then placed outdoors on the ground. During the fall and winter season the top surface of each slab was kept covered with water. When ice was frozen on the slabs calcium chloride was applied to the surface at the rate of 2.4 pounds per square yard. After the ice was completely thawed the surface was washed and fresh water left on the surface to await another freezing. A total of 80 cycles were obtained during three winter seasons: 1952–53, 17 cycles; 1953–54, 34 cycles; and 1954–55, 29 cycles. The slabs were rated periodically for surface scale.

Discussion of Test Results

The results of the tests for strength, volume change, and durability are shown in tables 3–5 and in figures 1–5. The data are discussed in relation to the effect of substituting in two percentages each of the four fly ashes for a portion of each of the two portland cements.

Effect on strength.—The flexural and compressive strengths of the concretes without fly ash and with fly ash replacing part of each cement are shown in table 3. This table also shows the relative strengths of concretes containing fly ash expressed as percentages of the strengths developed by the concrete without fly ash. These relative strengths for various ages of test are shown graphically in figures 1 and 2.

In the upper diagram of figure 1 are shown the relative compressive strengths of the non-air-entrained concretes made with cement A and containing the substitutions of the two percentages of each of the four fly ashes. The 7-day strengths of concretes containing fly ash ranged from 53 to 94 percent of the strength of comparable concrete without fly ash. At 28 days the concretes containing fly ash A or B were equal to or greater than the 28-day strength of the concrete without fly ash. The concretes containing fly ash X or Y at 28 days ranged in relative strength from 74 to 96 percent.

All of the non-air-entrained concrete con-

Table 3.—Results of strength and freezing and thawing tests [1]

Fly ash: Identification	Fly ash: Amount of replacement	Air	Modulus of rupture: 7 days	Modulus of rupture: 28 days	Modulus of rupture: 1 year	Compressive strength: 7 days	Compressive strength: 28 days	Compressive strength: 1 year	Relative strength [2]: Modulus of rupture: 7 days	Relative strength [2]: Modulus of rupture: 28 days	Relative strength [2]: Modulus of rupture: 1 year	Relative strength [2]: Compressive strength: 7 days	Relative strength [2]: Compressive strength: 28 days	Relative strength [2]: Compressive strength: 1 year	Air	Loss [3] in N² at— 10 cycles	25 cycles	50 cycles	100 cycles	150 cycles	175 cycles	200 cycles	Durability factor
Portland Cement A: Non-Air-Entrained Concrete																							
	Pct.	Pct.	P. s. i.	P. s. i.	P. s. i.	P. s. i.	P. s. i.	P. s. i.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	
None	----------	1.6	590	790	790	3,160	4,410	5,750	100	100	100	100	100	100	2.0	25	45 (24)	----------	----------	----------	----------	----------	6
A	16.7	1.5	525	740	835	2,930	4,480	6,300	89	94	106	93	102	110	2.8	22	54 (24)	----------	----------	----------	----------	----------	5
A	33.3	1.7	465	720	1,000	2,420	4,420	6,330	79	92	127	77	100	111	1.4	16	56 (24)	----------	----------	----------	----------	----------	5
B	16.7	1.5	550	790	955	2,970	4,640	6,640	93	100	121	94	105	115	1.3	24	57 (24)	----------	----------	----------	----------	----------	5
B	33.3	1.3	485	855	1,030	2,510	4,640	6,140	82	108	130	79	105	107	.8	16	48 (24)	----------	----------	----------	----------	----------	6
X	16.7	1.4	525	770	830	2,620	4,220	5,960	89	97	105	83	96	104	1.0	31	44 (14)	----------	----------	----------	----------	----------	4
X	33.3	1.2	360	665	880	1,900	3,350	5,770	61	84	111	60	76	100	1.5	41 (7)	----------	----------	----------	----------	----------	----------	2
Y	16.7	1.4	515	640	865	2,450	3,900	6,020	87	81	109	78	88	105	1.4	38 (7)	----------	----------	----------	----------	----------	----------	2
Y	33.3	1.4	355	610	835	1,690	3,270	4,970	60	77	106	53	74	86	1.7	51 (6)	----------	----------	----------	----------	----------	----------	1
Portland Cement A: Air-Entrained Concrete																							
None	----------	4.6	595	790	745	3,100	4,140	5,410	100	100	100	100	100	100	6.6	5	4	9	9	14	16	18	82
A	16.7	4.9	530	715	790	2,670	3,970	5,620	89	91	106	86	96	104	6.2	4	3	13	7	12	15	20	80
A	33.3	4.7	445	740	825	2,240	3,780	5,750	75	94	111	72	91	106	4.5	5	4	15	12	24	28	34	66
B	16.7	4.8	505	785	860	2,720	4,040	5,970	85	99	115	88	98	110	4.2	6	4	14	17	24	32	37	63
B	33.3	4.3	445	785	930	2,410	4,030	6,000	75	99	125	78	97	111	3.9	5	5	6	10	23	31	39	61
X	16.7	4.3	515	770	830	2,530	3,660	5,580	87	97	111	82	88	103	5.0	7	6	7	13	23	28	29	71
X	33.3	4.2	355	640	865	1,810	3,260	5,240	60	81	116	58	79	97	4.0	8	7	12	23	48 (150)	----------	----------	40
Y	16.7	4.8	470	660	760	2,230	3,490	5,410	79	84	102	72	84	100	5.8	5	5	6	6	14	18	19	81
Y	33.3	4.4	335	555	760	1,490	2,640	4,400	56	70	102	48	64	81	3.1	10	11	20	39 (86)	----------	----------	----------	25
Portland Cement B: Non-Air-Entrained Concrete																							
None	----------	1.3	705	880	850	3,770	5,890	7,480	100	100	100	100	100	100	1.3	4	9	42 (52)	----------	----------	----------	----------	15
A	16.7	1.4	640	790	935	3,150	5,220	8,690	91	90	110	84	89	116	.7	3	8	25	56 (85)	----------	----------	----------	19
A	33.3	1.6	535	815	1,025	2,390	4,460	8,250	76	93	121	63	76	110	.7	5	15	38 (52)	----------	----------	----------	----------	16
B	16.7	1.5	575	915	1,035	3,160	5,580	8,730	82	104	122	84	95	117	1.3	2	12	46 (48)	----------	----------	----------	----------	14
B	33.3	1.6	530	905	1,100	2,740	4,970	9,020	75	103	129	73	84	121	1.1	4	26	47 (34)	----------	----------	----------	----------	9
X	16.7	1.3	555	750	915	2,620	4,490	8,050	79	85	108	69	76	108	1.1	2	12	46 (48)	----------	----------	----------	----------	14
X	33.3	1.2	460	645	935	1,820	2,960	6,740	65	73	110	48	50	90	.8	9	36	44 (34)	----------	----------	----------	----------	9
Y	16.7	1.3	620	770	910	2,660	4,330	7,730	88	88	107	71	75	103	1.3	4	14	63 (48)	----------	----------	----------	----------	11
Y	33.3	1.4	425	690	995	1,750	3,130	6,570	60	78	117	46	53	88	1.6	36	51 (14)	----------	----------	----------	----------	----------	3
Portland Cement B: Air-Entrained Concrete																							
None	----------	4.6	700	775	750	3,840	5,480	6,270	100	100	100	100	100	100	5.4	2	4	4	4	9	8	9	91
A	16.7	4.4	650	730	860	3,320	4,800	7,260	93	94	115	86	88	116	4.9	1	3	5	1	9	7	14	86
A	33.3	4.8	495	750	900	2,590	4,200	7,110	71	97	120	67	77	113	5.6	0	3	1	2	8	7	7	93
B	16.7	4.5	600	750	875	3,450	5,290	7,540	86	97	117	90	97	120	4.7	0	5	1	5	6	11	14	86
B	33.3	4.4	570	805	875	2,850	4,510	7,440	81	104	117	74	82	119	5.2	0	7	2	7	7	8	9	91
X	16.7	4.9	575	735	825	2,860	4,490	6,710	82	95	110	74	82	107	5.6	0	4	2	8	6	7	9	91
X	33.3	4.8	445	635	835	1,970	3,310	5,700	64	82	111	51	60	91	5.6	0	2	4	6	11	14	16	84
Y	16.7	4.2	555	745	825	2,870	4,400	6,500	79	96	110	75	80	104	3.1	0	4	6	5	6	8	8	92
Y	33.3	4.3	370	605	780	1,840	2,870	5,420	53	78	104	48	52	86	3.7	0	4	8	7	15	16	16	84

[1] Each value for mixes without fly ash is an average of six tests; for mixes containing fly ash, each value is an average of three tests.
[2] Based on strength of concrete without fly ash.
[3] Figures in parentheses indicate number of cycles at which final reading was taken.

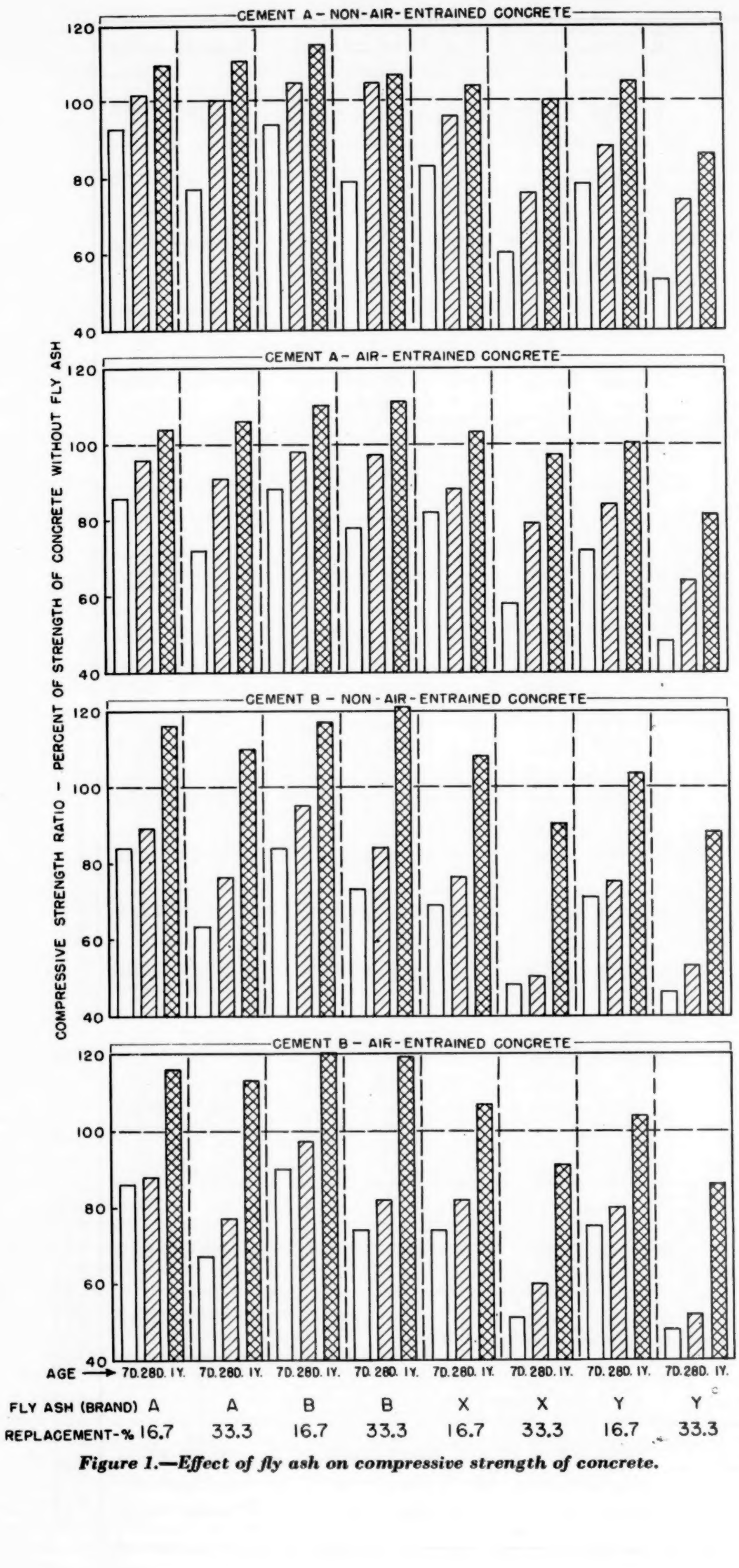


Figure 1.—Effect of fly ash on compressive strength of concrete.

taining cement A and fly ash equaled or exceeded the strength of comparable concrete without fly ash at 1 year, with the exception of that containing 33⅓ percent of fly ash Y. The concrete containing 33⅓ percent of fly ash Y had a relative strength of 86 percent of the comparable concrete without fly ash. The highest relative strength at 1 year for concrete made with cement A was 115 percent.

The three remaining diagrams in figure 1 show a pronounced similarity in the relative strength to that shown in the first diagram. This is also apparent in table 4 which shows the ranges and averages of relative strengths.

It is significant that the 7-day compressive strengths of the concretes containing fly ash are lower in each case than the comparable concrete without fly ash. With the exception of cement A, non-air-entrained concrete containing fly ash A or B, the same relation is found at 28 days. For the fly ashes of low carbon content, both replacements of cement with fly ash resulted in greater concrete strengths at 1 year than for concrete without fly ash. In one case, the increase in strength was 21 percent. Replacement of 16⅔ percent of the cement with fly ashes X and Y resulted in somewhat lower relative strengths at 1 year, but in all cases these were equal to or greater than 100 percent. Concretes containing 33⅓ percent of high carbon fly ashes (X or Y) had strengths less than the concrete without fly ash at all ages including 1 year, except fly ash X, used as replacement for cement A in non-air-entrained mixes; the latter had approximately the same strength at 1 year.

The use of air entrainment appeared to have little effect on the relative strengths, particularly with cement B. For each combination of cement and fly ash, the concrete with and without air entrainment had similar relative compressive strengths.

Figure 2 gives a comparison of the relative flexural strengths. The same general relation shown for compressive strengths exists for the flexural strengths, as is apparent in table 4, except that in no case did the concrete with the fly ash substitutions fail to equal the flexural strength of the concrete without fly ash at the 1-year period.

Durability.—The data from the freezing and thawing tests are shown in table 3 and in figures 3–4. In table 3 are shown the losses in natural frequency squared (N^2) at 10, 25, 50, 100, 150, 175, and 200 cycles and the durability factor.

The reductions in N^2 plotted against the number of cycles in figure 3 show that all the concretes containing fly ash and without air-entrainment deteriorated very rapidly under freezing and thawing. With two exceptions all air-entrained concrete with and without fly ash substitutions withstood 200 cycles with a reduction in N^2 of less than 40 percent. The exceptions were the concretes made from cement A and containing 33⅓ percent of fly ashes X and Y which had air contents of 4.0 and 3.1 percent, respectively.

In order to express in a single factor the loss in N^2 as related to the number of cycles of freezing and thawing required to produce that loss, a value known as the durability factor (*DF*) is used.[3] The values for durability factor shown in table 3 are calculated as follows:

$$DF=\frac{PN}{M}$$

Where:

DF=durability factor of the test specimens.

P=relative dynamic modulus of elasticity at N cycles in percent.

N=number of cycles at which P reached 60 percent or 200, whichever is less.

M=200.

The durability factors and the air contents of the concrete are shown graphically in figure 4. To insure satisfactory resistance of the concrete to the alternate freezing and thawing in the type of freezing test used, the durability factor should be 50 or greater. Durability factors for the concretes without entrained air were all less than 20. All the concretes without air made with cement A had durability factors of 8 or less.

Of the 18 concretes in which air was entrained only 2 had durability factors of less than 60. The two concretes contained portland cement A and high carbon fly ashes: one with 33⅓ percent of fly ash X, and the other, 33⅓ percent of fly ash Y. The comparable concretes made with cement B had durability factors in excess of 80. For air-entrained concrete containing cement A with fly ash substitutions there appears to be a general relation between air content and the durability factor, the higher air content being associated with greater durability. This relation was not apparent for cement B.

It should be pointed out here that it was very difficult to obtain a uniform air content because concretes with the high carbon fly ashes required such large amounts of the air-entraining admixture to give the desired air content. Although the air content of the concrete in all cases was raised above 3 percent by the use of excessive quantities of the air-entraining admixture, the concrete containing fly ash X used as a replacement for 33⅓ percent of cement A with an air content of 4.0 percent had a durability factor of 40; concrete containing fly ash Y with 3.1 percent of entrained air had a durability factor of 25. In the concretes in which 16⅔ percent of cement A was replaced with fly ashes X and Y, the air contents were 5.0 and 5.8 percent and the durability factors were 71 and 81, respectively.

The durability factors for all air-entrained concretes made with cement B were 84 or above, even though the concrete with 16⅔ percent of fly ash Y had an air content of only 3.1 percent.

[3] See tentative method of test for *Resistance of concrete specimens to slow freezing and thawing in water or brine,* ASTM Designation C 292-52T. ASTM Standards 1955, part 3, pp. 1347-1350.

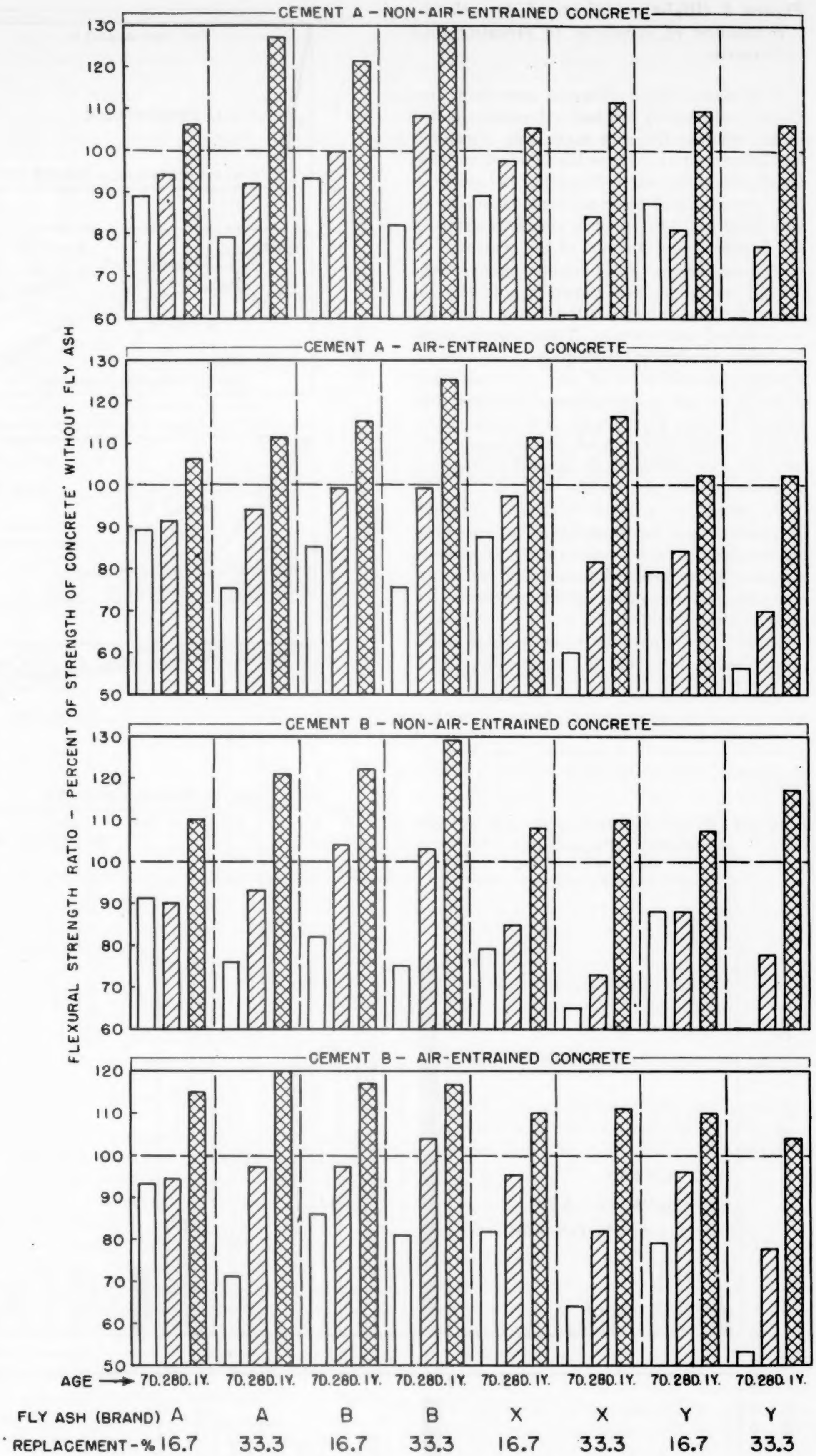
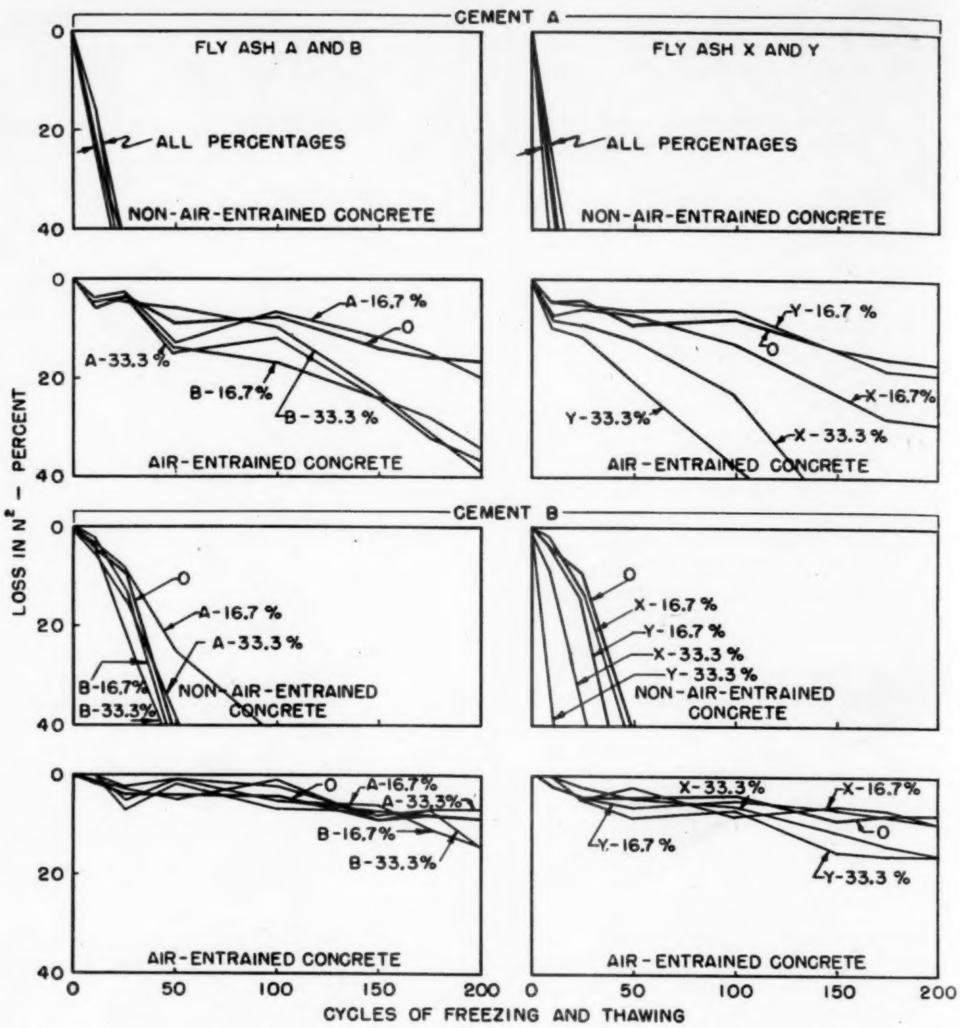


Figure 2.—Effect of fly ash on flexural strength of concrete.

Figure 3* (Right).—*Effect of fly ash on resistance of concrete to freezing and thawing.



The air-entrained concrete containing cement A without fly ash had a durability factor of 82, whereas the mix containing cement B had a factor of 91. These high factors indicate very little difference in durability between the two cements and offer no explanation as to why they act differently in concrete when fly ash is substituted for part of the cement.

Volume change.—The volume change data for all concretes are shown graphically in figure 5. The values plotted in the diagrams were actual test values. These curves show that there is very little difference in the volume change characteristics of the concrete made without fly ash substitutions and those containing various percentages of fly ash. Also, those containing the higher percentages of fly ash had less shrinkage in general than those with the smaller percentages of fly ash.

Resistance to scaling.—Calcium chloride, frequently used for thawing ice on concrete pavements, has been found to be very injurious to non-air-entrained concrete.[4] Air-entrained concrete usually offers good resistance to attack from chloride salts.

Table 5 shows periodic visual ratings of exposure slabs at 12, 17, 39, 51, and 80 cycles.

[4] *Resistance of concrete surfaces to scaling action of ice-removal agents*, by Albert G. Timms, Highway Research Board Bulletin 128, 1956, pp. 20–50; also *Factors affecting resistance of portland cement concrete to scaling action of thawing agents*, by same author, PUBLIC ROADS, vol. 28, No. 7, Apr. 1955, pp. 143–157.

Figure 4* (Below).—*Effect of fly ash on durability of concrete.

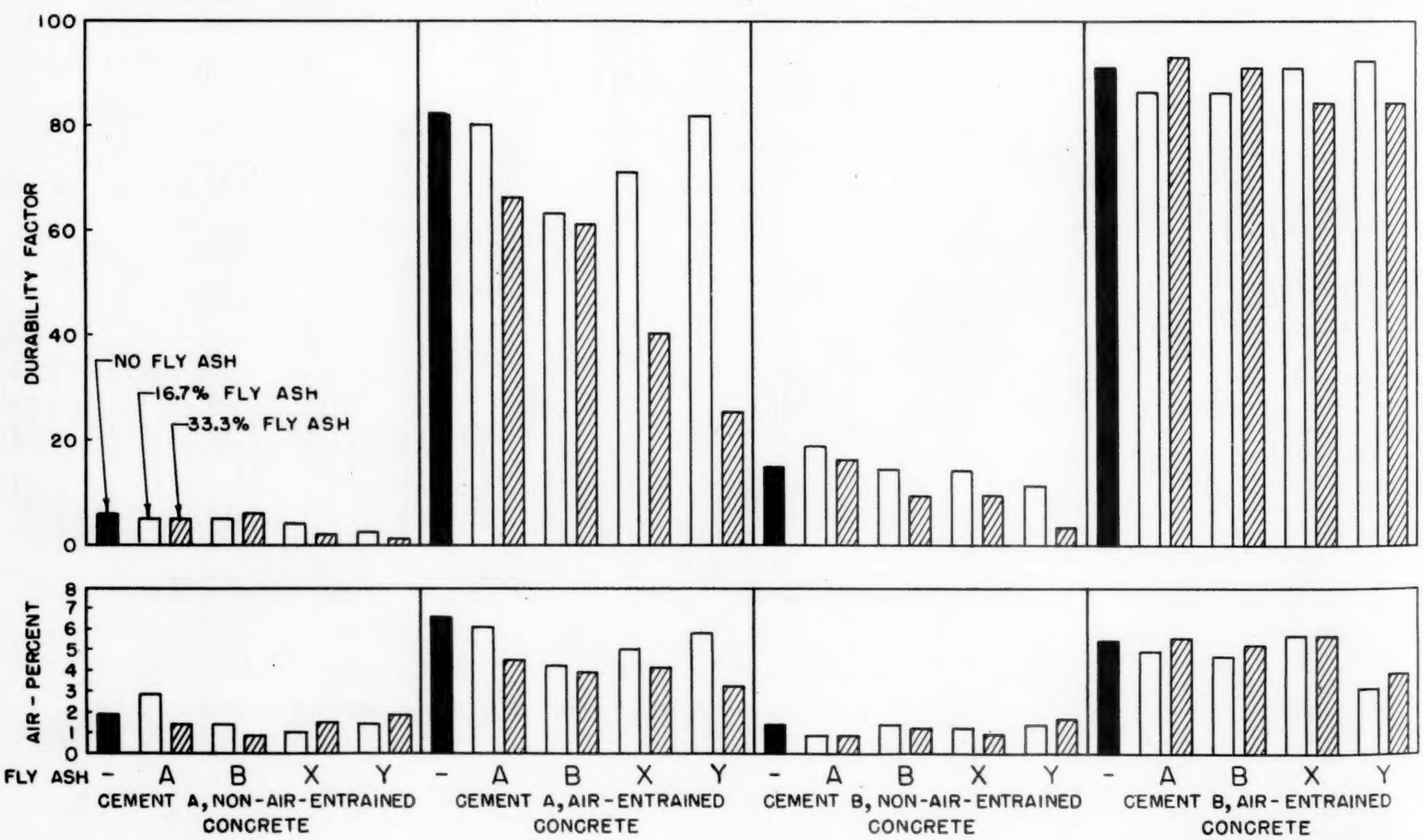


Table 4.—Relative compressive and flexural strengths of concrete containing fly ash

Cement	Type of concrete	Fly ash replacement	Relative compressive strengths at—						Relative flexural strengths at—					
			7 days		28 days		1 year		7 days		28 days		1 year	
			Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
		Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
A	Non-air-entrained	16.7	94–78	87	105–88	98	115–104	108	93–87	90	100–81	93	121–105	110
	do	33.3	79–53	67	105–74	89	111–86	101	82–60	70	108–77	90	130–106	118
	Air-entrained	16.7	88–72	82	98–84	92	110–100	104	89–79	85	99–84	93	115–102	108
	do	33.3	78–48	64	97–64	83	111–81	99	75–56	66	99–70	86	125–102	113
B	Non-air-entrained	16.7	84–69	77	95–75	84	117–103	111	91–79	85	104–85	92	122–107	112
	do	33.3	73–46	58	84–50	66	121–88	102	76–60	69	103–73	87	129–110	119
	Air-entrained	16.7	90–74	81	97–80	87	120–104	112	93–79	85	97–94	96	117–110	113
	do	33.3	74–48	60	82–52	68	119–86	102	81–53	67	104–78	90	120–104	113

Table 5.—Visual ratings of surface scaling of concrete slabs [1] exposed to action of calcium chloride

Fly ash		Air [2]	Rating after exposure to outdoor freezing and thawing with $CaCl_2$ for—				
Identification	Amount of replacement		12 cycles	17 cycles	39 cycles	51 cycles	80 cycles
Portland Cement A: Non-Air-Entrained Concrete							
	Percent	*Percent*					
None	------	1	5	8	10	10	10
A	33.3	1	6	8	10	10	10
B	33.3	1	6	8	10	10	10
X	33.3	1	7	8	10	10	10
Y	33.3	1	6	8	10	10	10
Portland Cement A: Air-Entrained Concrete							
None	------	4.0	1	2	2	3	4
A	33.3	4.6	2	4	3	4	5
B	33.3	5.4	3	4	4	5	7
X	33.3	4.9	4	6	7	8	8
Y	33.3	4.3	4	6	6	8	8
Portland Cement B: Non-Air-Entrained Concrete							
None	------	1	3	8	10	10	10
A	33.3	1	4	8	9	10	10
B	33.3	1	4	8	10	10	10
X	33.3	1	6	8	10	10	10
Y	33.3	1	5	8	10	10	10
Portland Cement B: Air-Entrained Concrete							
None	------	6.8	1	2	2	2	3
A	33.3	4.0	1	2	4	4	5
B	33.3	3.3	5	6	7	8	8
X	33.3	3.9	6	8	8	8	8
Y	33.3	5.8	6	8	8	8	9

[1] Specimens were 4- by 16- by 24-inch slabs.
[2] Mix is same as used for freezing and thawing specimens except for air content.

The numerical significance of the ratings is as follows:

0—No scaling.
1—Very light spotted scale.
2—Spotted scale.
3—Light scale over about one-half the surface.
4—Light scale over most of surface.
5—Light scale over most of surface, few moderately deep spots.
6—Moderately deep scale spotted.
7—Moderately deep scale over one-half the surface.
8—Moderately deep scale over entire surface.
9—Deep scale spotted, otherwise moderate scale.
10—Deep scale over entire surface.

The concretes without air-entrainment and without fly ash had very poor resistance to attack by the chloride salt. None of the fly ashes used as replacements for part of the cement were effectual in improving the resistance of non-air-entrained concrete to attack by calcium chloride.

Entrained air greatly increased the resistance of the concrete without fly ash. In air-entrained concrete all the fly ash replacements for cement were detrimental to the resistance to scaling of the concrete, as indicated by the ratings of 3 to 8 at 39 cycles as compared with 2 for the concretes without fly ash. The extent of attack by calcium chloride did not appear to differ much with the brand of cement or with the fly ash used as a replacement.

It would appear from these data that if there is a possibility that calcium chloride might be used for ice removal, the use of fly ash as a substitute for portland cement in the concrete in the percentage used in this investigation is questionable.

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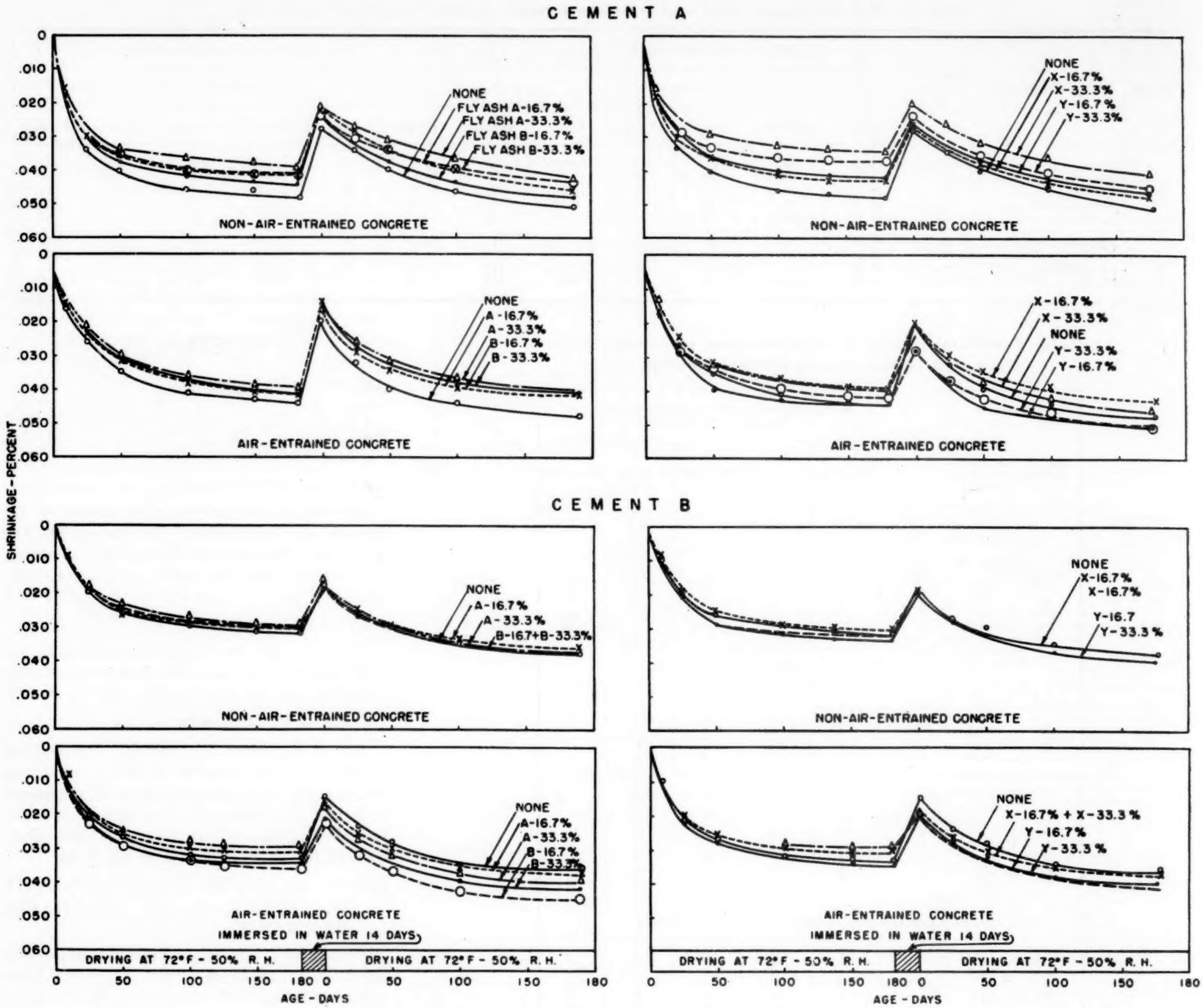

Figure 5.—Effect of fly ash on drying shrinkage of concrete.

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Labor Usage in Highway Construction as Influenced by Improved Equipment

BY THE CONSTRUCTION BRANCH
BUREAU OF PUBLIC ROADS

Reported by EDWIN J. COPPAGE, JR., Chief, Construction Management Section, and EDWIN L. STERN, Supervising Highway Engineer

LABOR USAGE DATA collected by the Bureau of Public Roads since 1944 indicate a pronounced decrease in the number of man-hours of direct labor required for a given physical volume of highway construction. Direct labor is defined as labor employed by the contractor at or near the site of the project. Indirect labor is that employed in the off-site production, manufacture or shipment of materials, supplies or equipment used, and labor induced by the re-spending of wages earned on the project.

The decrease in man-hour usage, which is illustrated in figures 1 and 2, is basically due to increased productivity of the labor-equipment combination resulting from great strides that have been made by manufacturers in developing more efficient construction equipment.

The curve in figure 1 shows the trend of man-hour usage per million dollars of construction cost from 1944 to 1955 and projected to 1970. The data for the plotted points are based on labor usage and contract costs reported by contractors for Federal-aid highway construction projects. The projected trend for the years 1955–70 was made by deriving an empirical formula for a smooth curve to fit the plotted points from 1944 to 1954. From a value of approximately 217,700 man-hours per million dollars construction cost in 1944, the factor had decreased 43 percent to about 123,000 in 1955. The projected curve indicates values of 104,000 for 1960 and 80,000 for 1970.

Since a million dollars purchased a different physical volume of work each year, due to varying price levels, the factors have been adjusted by means of the Bureau of Public

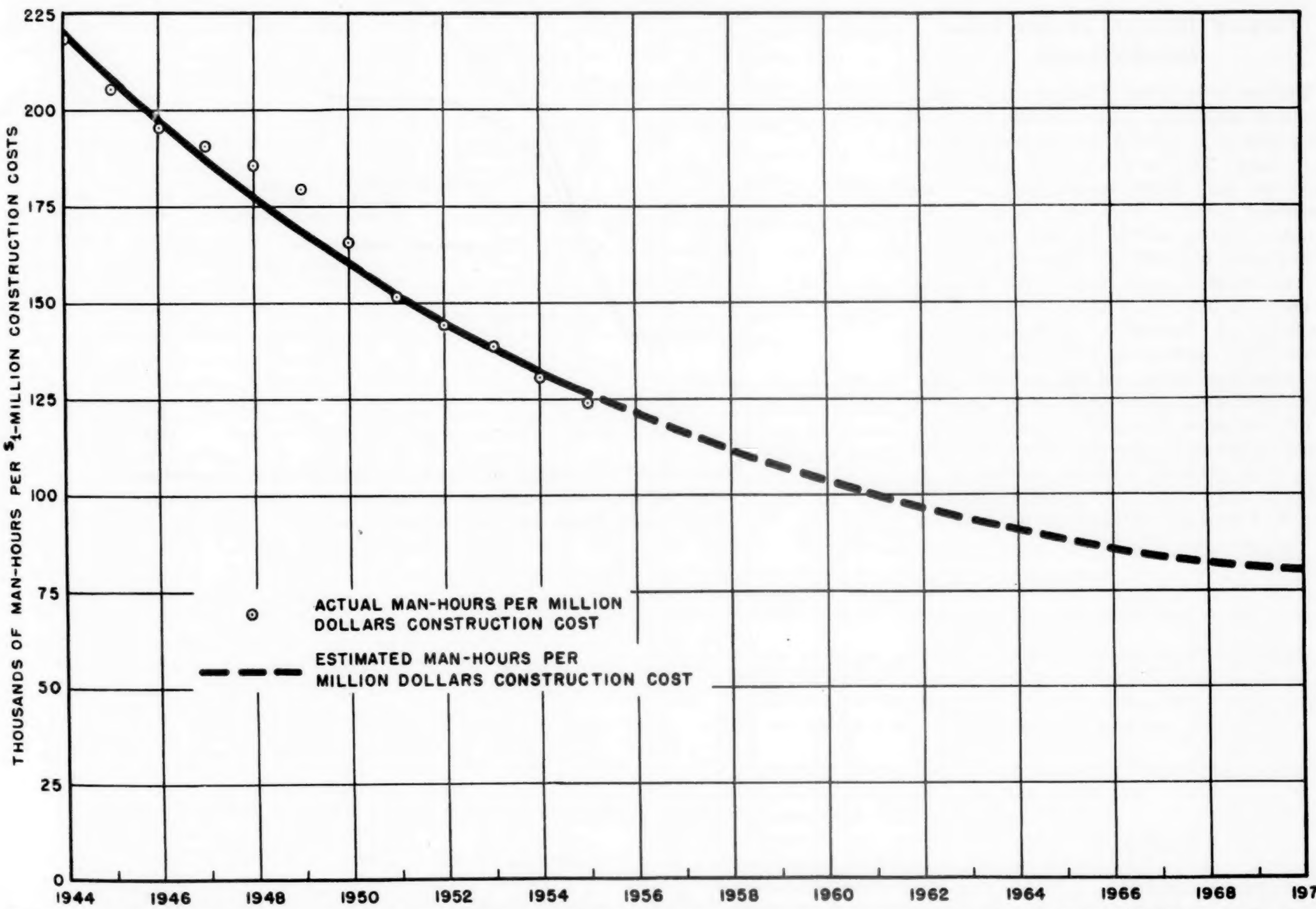

Figure 1.—Man-hours of labor required per million dollars of highway construction expenditures, adjusted to 1954 bid price level and excluding right-of-way and engineering costs.

Table 1.—Comparison between physical volume of all highway construction and highway construction labor usage

Calendar year	Physical volume		Labor usage	
	Construction expenditures [1]	Index, 1944=100	Man-hours	Index, 1944=100
	Billions		*Millions*	
1944	$C. 448	100. 0	97. 6	100. 0
1945	. 459	102. 5	94. 3	96. 5
1946	. 986	220. 1	193. 4	198. 1
1947	1. 590	354. 9	305. 7	313. 0
1948	1. 823	406. 9	342. 4	350. 6
1949	2. 062	460. 3	369. 2	378. 2
1950	2. 263	505. 1	374. 8	383. 8
1951	2. 434	543. 3	370. 6	379. 5
1952	2. 594	579. 0	374. 9	384. 0
1953	2. 908	649. 1	399. 8	409. 5
1954	3. 659	816. 7	474. 5	486. 0
1955	3. 962	884. 4	488. 8	500. 6

[1] Construction expenditures, adjusted to 1954 bid price level, exclude costs of right-of-way and engineering.

Roads highway construction price index to show for each year, the man-hours required to produce a physical volume of construction equivalent to that which could be purchased for a million dollars in 1954.

The practical application of the labor usage factors is found in estimating manpower requirements for various size highway construction programs and in evaluating changes in productivity and the effect of such changes on highway construction prices.

Factors Affecting Future Labor Requirements

The curve in figure 1 is plotted to follow the more significant known points, the trend of which is projected to represent future potentials. The actual factors, subsequent to 1955, may differ appreciably from the projected curve if there are changes in the trends of labor and equipment availability, in the trend of equipment improvement, and in the trend of wage rates. For example, in case of a scarcity of labor, it would be the tendency of contractors to increase their usage of labor-saving equipment, thus lowering the man-hour factor. If the trend in equipment improvement becomes more pronounced, a reduced labor factor will result. A pronounced increase in the wage-rate trend could have the effect of causing contractors to increase their usage of improved equipment, thereby lowering the man-hour usage factor. A decrease in the wage-rate trend could have the opposite effect.

The annual labor usage factors shown in figure 1 have been used in deriving the estimated labor requirements for all highway construction during the 13-year period, 1957–69. To bring all highway systems up to adequacy, as determined by the nationwide highway needs study published in 1955, 8.2 billion man-hours of labor would be required during the 13-year period, or an average annual labor force of about 396,000 workers, assuming 1,600 man-hours per year per worker.

Increased Productivity, 1944–55

Figure 2 and table 1 show the relation, each year, from 1944 through 1955, between the physical volume of all highway construction performed and the number of man-hours of labor used. These data indicate that the construction volume in 1955 was nearly nine times that for 1944, while labor usage in 1955 was five times that for 1944. The divergence between the two curves in figure 2 is indicative of increased productivity of the labor-equipment combination.

The 43-percent reduction in labor usage factors since 1944 is equivalent to a similar reduction in contractors' labor costs. During the period 1944–55, construction bid prices increased about 35 percent. Had there been no reduction in labor usage factors, the bid price increase during this period would have been approximately 61 percent.

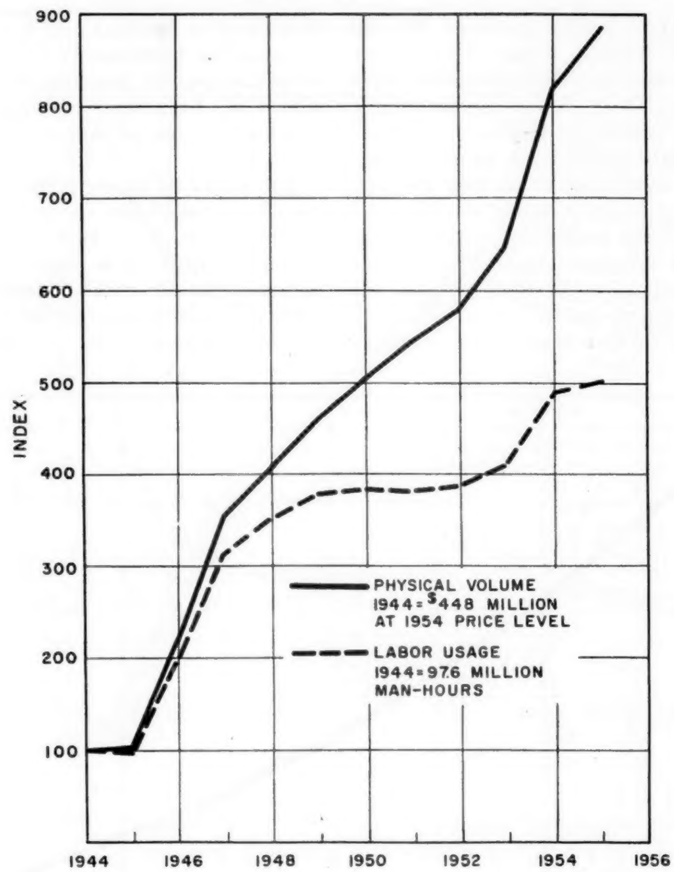

Figure 2.—Comparison between physical volume (excluding right-of-way and engineering costs) of all highway construction and highway construction labor usage.

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Construction of Private Driveways, No. 272MP (1937). 15 cents.
Criteria for Prestressed Concrete Bridges (1954). 15 cents.
Design Capacity Charts for Signalized Street and Highway Intersections (reprint from PUBLIC ROADS, Feb. 1951). 25 cents.
Electrical Equipment on Movable Bridges, No. 265T (1931). 40 cents.
Factual Discussion of Motortruck Operation, Regulation, and Taxation (1951). 30 cents.
Federal Legislation and Regulations Relating to Highway Construction (1948). Out of print.
Financing of Highways by Counties and Local Rural Governments: 1931–41, 45 cents; 1942–51, 75 cents.
General Location of the National System of Interstate Highways, Including All Additional Routes at Urban Areas Designated in September 1955. 55 cents.
Highway Bond Calculations (1936). 10 cents.
Highway Bridge Location No. 1486D (1927). 15 cents.
Highway Capacity Manual (1950). $1.00.
Highway Needs of the National Defense, House Document No. 249 (1949). 50 cents.
Highway Practice in the United States of America (1949). 75 cents.
Highway Statistics (annual):
1945 (out of print). 1949, 55 cents. 1953, $1.00.
1946, 50 cents. 1950 (out of print). 1954, 75 cents.
1947, 45 cents. 1951, 60 cents.
1948, 65 cents. 1952, 75 cents.
Highway Statistics, Summary to 1945. 40 cents.
Highways in the United States, *nontechnical* (1954). 20 cents.
Highways of History (1939). 25 cents.
Identification of Rock Types (reprint from PUBLIC ROADS, June 1950). 15 cents.
Interregional Highways, House Document No. 379 (1944). 75 cents.
Legal Aspects of Controlling Highway Access (1945). 15 cents.
Local Rural Road Problem (1950). 20 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways (1948) (*including 1954 revisions supplement*). $1.25.
Revisions to the Manual on Uniform Traffic Control Devices for Streets and Highways (1954). *Separate*, 15 cents.

PUBLICATIONS (Continued)

Mathematical Theory of Vibration in Suspension Bridges (1950). $1.25.
Model Traffic Ordinance (revised 1953). Out of print.
Needs of the Highway Systems, 1955–84, House Document No. 120 (1955). 15 cents.
Opportunities in the Bureau of Public Roads for Young Engineers (1955). 25 cents.
Parking Guide for Cities (1956). 55 cents.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft (1943). $2.00.
Progress and Feasibility of Toll Roads and Their Relation to the Federal-Aid Program, House Document No. 139 (1955). 15 cents.
Public Control of Highway Access and Roadside Development (1947). 35 cents.
Public Land Acquisition for Highway Purposes (1943). 10 cents.
Public Utility Relocation Incident to Highway Improvement, House Document No. 127 (1955). 25 cents.
Results of Physical Tests of Road-Building Aggregate (1953). $1.00.
Roadside Improvement, No. 191MP (1934). 10 cents.
Selected Bibliography on Highway Finance (1951). 60 cents.
Specifications for Aerial Surveys and Mapping by Photogrammetric Methods for Highways, 1956: a reference guide outline. 55 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks, FP-41 (1948). $1.50.
Standard Plans for Highway Bridge Superstructures (1956). $1.75.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces (1943). 10 cents.
Transition Curves for Highways (1940). $1.75.

MAPS

State Transportation Map series (available for 39 States). Uniform sheets 26 by 36 inches, scale 1 inch equals 4 miles. Shows in colors Federal-aid and State highways with surface types, principal connecting roads, railroads, airports, waterways, National and State forests, parks, and other reservations. Prices and number of sheets for each State vary—see Superintendent of Documents price list 53.
United States System of Numbered Highways. 28 by 42 inches, scale 1 inch equals 78 miles. 20 cents.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

Bibliography on Automobile Parking in the United States (1946).
Bibliography on Highway Lighting (1937).
Bibliography on Highway Safety (1938).
Bibliography on Land Acquisition for Public Roads (1947).
Bibliography on Roadside Control (1949).
Express Highways in the United States: a Bibliography (1945).
Indexes to PUBLIC ROADS, volumes 17–19 and 23.
Title Sheets for PUBLIC ROADS, volumes 24–28.

DEPARTMENT OF COMMERCE - BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF DECEMBER 31, 1956

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$30,173	$40,511	$30,060	470.1	$10,255	$6,941	65.2	$61,876	$37,214	672.9	$112,642	$74,215	1,208.2
Arizona	31,274	10,690	8,521	155.6	5,839	4,260	41.9	10,414	7,966	100.5	26,943	20,747	298.0
Arkansas	41,965	19,868	11,264	494.9	8,418	4,488	77.4	29,016	18,149	316.1	57,302	33,901	888.4
California	77,938	45,461	29,729	225.8	40,166	30,022	55.3	283,150	138,558	238.8	368,777	198,309	519.9
Colorado	44,286	9,784	5,487	105.7	5,093	3,124	35.0	27,815	18,718	156.0	42,692	27,329	296.7
Connecticut	40,656	13,060	8,800	5.8	7,528	6,511	9.7	8,241	4,320	13.7	28,829	19,631	29.2
Delaware	23,009	1,870	935	24.9	832	449	9.6	10,153	5,128	47.8	12,855	6,512	82.3
Florida	48,114	14,034	7,450	248.8	13,547	6,935	54.9	53,319	30,692	325.5	80,900	45,077	629.2
Georgia	75,916	34,889	18,428	501.5	9,930	5,584	55.4	70,369	37,740	750.1	115,188	61,752	1,307.0
Idaho	35,658	3,332	2,182	41.9	3,706	2,407	31.5	13,490	9,194	164.3	20,528	13,783	237.7
Illinois	80,094	65,968	44,176	443.9	28,299	19,646	55.3	145,689	98,453	660.8	239,956	162,275	1,160.0
Indiana	98,335	24,747	13,386	97.0	6,247	3,464	48.5	36,861	20,888	147.8	67,855	37,738	293.3
Iowa	35,579	47,226	32,610	775.1	15,835	10,992	100.3	33,362	20,676	814.8	96,423	64,278	1,690.2
Kansas	27,938	39,376	32,851	655.4	5,284	2,798	62.9	39,148	22,982	1,036.6	83,808	58,631	1,754.9
Kentucky	64,981	7,247	4,113	95.5	343	190	1.3	39,455	23,311	306.8	47,045	27,614	403.6
Louisiana	47,968	39,066	18,603	145.3	7,853	4,148	9.9	37,455	20,084	254.5	84,374	42,835	409.7
Maine	28,682	7,097	3,832	42.5	1,525	917	9.1	16,139	8,436	99.0	24,761	13,185	150.6
Maryland	12,066	26,456	15,266	87.6	13,937	11,000	16.8	51,883	32,498	139.6	92,276	58,764	244.0
Massachusetts	43,141	38,536	22,829	31.6	38,226	23,362	26.7	50,811	28,437	47.2	127,573	74,628	105.5
Michigan	83,560	61,018	38,375	459.1	22,704	13,758	56.0	59,118	36,007	257.1	142,840	88,140	772.2
Minnesota	50,065	23,986	17,712	316.1	9,165	6,207	78.2	47,342	29,005	783.6	80,493	52,924	1,177.9
Mississippi	47,650	21,396	11,139	569.8	8,190	6,125	98.9	27,473	15,410	481.4	57,059	32,674	1,150.1
Missouri	56,616	35,226	20,343	1,186.7	21,086	16,247	83.4	91,608	52,005	929.2	147,920	88,595	2,199.3
Montana	55,502	8,522	5,288	173.7	5,005	3,024	66.8	29,283	18,411	388.7	42,810	26,723	629.2
Nebraska	62,755	3,904	2,280	131.4	4,260	2,677	42.5	22,167	11,398	805.0	30,331	16,355	978.9
Nevada	39,594	1,625	1,356	29.7	1,571	1,362	14.8	12,156	10,305	134.9	15,352	13,023	179.4
New Hampshire	16,913	9,344	6,100	43.7	1,869	1,167	8.3	11,222	6,748	42.7	22,435	14,015	94.7
New Jersey	88,545	12,556	6,278	62.8	5,219	2,608	1.7	36,313	18,154	47.2	54,088	27,040	111.7
New Mexico	14,717	21,006	18,486	93.0	5,650	4,959	39.6	20,940	15,238	195.7	47,596	38,683	328.3
New York	186,776	13,946	7,153	49.1	69,945	47,470	39.9	274,121	147,693	338.8	358,012	202,316	427.8
North Carolina	89,834	13,635	7,435	150.9	7,307	3,999	37.4	51,031	24,950	664.9	71,973	36,384	853.2
North Dakota	21,715	24,838	20,410	777.0	6,326	3,762	255.5	14,561	7,916	652.6	45,725	32,088	1,685.1
Ohio	82,140	47,006	30,677	119.2	61,843	45,406	97.8	108,986	65,538	145.4	217,835	141,621	362.4
Oklahoma	32,244	53,638	35,815	536.7	10,037	5,553	55.4	48,272	27,618	417.4	111,947	68,986	1,009.5
Oregon	30,692	9,273	7,229	60.1	3,773	2,846	12.8	36,031	25,011	195.3	49,077	35,086	268.2
Pennsylvania	152,633	36,901	19,410	88.0	73,494	51,315	68.2	113,056	57,538	330.7	223,451	128,263	486.9
Rhode Island	14,465	3,692	1,958	7.3	2,698	2,322	.3	26,922	16,118	23.9	33,312	20,398	31.5
South Carolina	39,232	26,746	17,290	525.7	4,291	3,017	19.5	27,586	14,913	529.8	58,623	35,220	1,075.0
South Dakota	26,938	27,605	18,809	576.5	2,723	1,524	104.3	16,308	9,586	556.9	46,636	29,919	1,237.7
Tennessee	50,630	27,507	13,142	572.2	13,969	6,985	56.8	78,484	47,806	403.2	119,960	67,933	1,032.2
Texas	155,635	20,328	10,403	356.3	45,542	33,271	262.6	131,490	75,028	1,354.0	197,360	118,702	1,972.9
Utah	21,643	18,325	15,168	137.0	817	638	1.9	8,153	6,320	134.0	27,295	22,126	272.9
Vermont	14,417	7,453	5,148	29.1	287	224		12,655	8,340	49.0	20,395	13,712	78.1
Virginia	68,806	20,286	11,873	142.7	6,699	3,705	19.4	34,413	17,879	327.5	61,398	33,457	489.6
Washington	54,821	5,845	3,819	73.0	6,925	4,181	66.1	31,051	18,036	196.1	43,821	26,036	335.2
West Virginia	46,589	16,124	8,485	47.3	6,255	3,140	24.3	23,457	11,878	72.5	45,836	23,503	144.1
Wisconsin	70,712	11,171	5,871	160.7	8,306	4,180	47.2	54,451	32,474	290.8	73,928	42,525	498.7
Wyoming	7,380	24,048	19,474	204.7	7,957	6,464	65.3	20,587	14,866	235.3	52,592	40,804	505.3
Hawaii	7,178	1,444	716	2.8	3,168	1,568	4.9	4,481	2,122	7.7	9,093	4,406	15.4
District of Columbia	22,554	11,581	7,281	4.2	842	437		9,208	5,853	.1	21,631	13,571	4.3
Puerto Rico	11,831	7,153	3,042	23.5				21,007	9,780	59.5	28,160	12,822	83.0
Alaska	15,074												
TOTAL	2,627,629	1,116,346	708,487	12,358.9	650,786	437,379	2,496.5	2,522,579	1,443,388	17,343.7	4,289,711	2,589,254	32,199.1